VOLUME VI. }
NUMBERS 6-7 }

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JUNE AND JULY, 1889.

Annual Subscriptions to Institutions $5.00.
Single Copies - 50 cts.

DOUBLE NUMBER.

# TRANSACTIONS

OF THE

# AMERICAN INSTITUTE

OF

# ELECTRICAL ENGINEERS.

GENERAL MEETING, MAY 22D, 1889.

(MORNING SESSION.)

SUBJECTS:

**Some Results with Secondary Batteries in Train Lighting.**

ALEXANDER S. BROWN.

**The Inherent Defects of Lead Storage Batteries.**

DR. LOUIS DUNCAN.

**Electric Motor Regulation.**

FRANCIS B. CROCKER.

NEW YORK CITY:
PUBLISHED BY THE INSTITUTE, UNDER THE SUPERVISION OF THE EDITING COMMITTEE.
R. W. POPE, *Secretary*,
TEMPLE COURT, 5 BEEKMAN STREET.

# [illegible] OF THE [illegible]

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*A paper read before the American Institute of Electrical Engineers, New York, May 22d, 1889, and discussion thereon.*

# SOME RESULTS WITH SECONDARY BATTERIES IN TRAIN LIGHTING.

BY ALEXANDER S. BROWN.

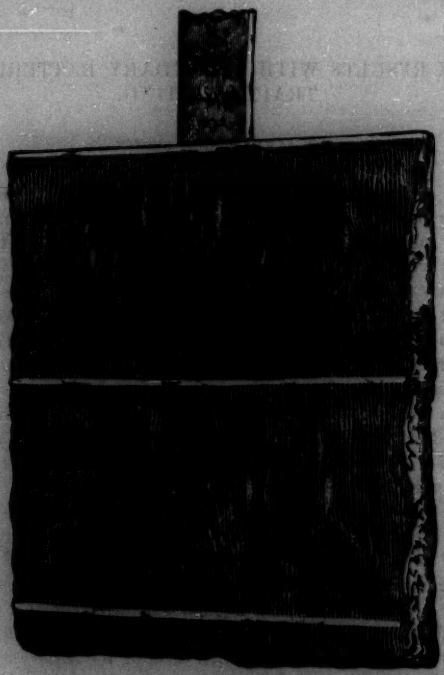
The arguments in favor of the incandescent electric light for railway passenger trains are so well understood by the members of the Institute, from their own general knowledge of the subject, as well as from papers previously presented, that it is unnecessary for me to allude to its admitted superiority over either gas, oil or candles. It is now four years since the Pennsylvania Railroad Company, appreciating the advantages of electric lighting for this purpose, began a series of experiments with the secondary battery, for the illumination of parlor cars.

I am unable to give the cost of lighting by any of the batteries referred to, as the expense appears to have been a secondary consideration compared with the necessity of securing the best system of illumination.

The first experiments made by the company were with the Faure accumulator, which was brought to this country from France in the spring or early in the summer of 1882, and put on passenger coach No. 397 in August of that year. The car was run for a few days only, but enough was learned in that time to show that the lighting of cars by secondary batteries was perfectly practicable, when a modified form of the battery could be obtained.

During the summer of 1884, experiments with the Brush storage batteries were commenced at the Altoona shops of the Pennsylvania Railroad, and continued through the fall and winter of that year. These experiments were made by Dr. Dudley, and proved so successful that eight parlor cars which were being constructed at that time were equipped for incandescent lighting, and put into regular service on the 1st of April, 1885.

The Brush cells used consisted of three plates each, two negative and one positive, the amount of surface of the positive plate being equal to that of both the negatives. These plates differed from those now used, there being no paste in their composition. The negative plate shows the form of construction, and was designed to give the greatest possible amount of surface from



NEGATIVE PLATE, BRUSH CELL.

the least weight of material. The positive plate measured $8 \times 9 \times 1$ inches, and the negative, $8 \times 9 \times \frac{1}{2}$ inches.

These batteries were rated at seventy ampere-hours, but the hard usage they received soon reduced their capacity, and at the end of a year's time the positive plates were almost entirely destroyed. In fact, I have taken plates out of the cells which had

holes in them fully four inches in diameter, while the deposit in the bottom of the cell would be from an inch to an inch and a half in depth. The plates also had a decided tendency both to buckle and grow, and in a number of cases it was a very difficult matter to remove the plates without injury to the cell; you will understand, of course, that I allude more particularly to the positive plate. The weak points in the Brush battery were the small number of ampere-hours per pound of material—about two, I believe. There was a tendency to buckle and sulphate, and the arrangement for connecting the plates was such that there was oxidation at the junction, causing the plates to break when subject to the motion of the car. This last feature was a source of endless trouble to us, and as is usually the case, was sure to happen at a time or place where it was impossible to repair the break. While using the Brush battery the cars were wired with the battery boxes, one on each side of the car, coupled together in series, each box holding three trays, and each tray containing four cells, this giving a total of twenty-four cells to a car, or a current of forty-eight volts. The lamps used originally were of the Brush-Swan type, with small platinum loops projecting from the base, these hooking into a socket and held in place by a spiral spring, this socket fitting into another one, to which the connections to the wires were made.

After using this style for some time an improved pattern of Brush-Swan lamp was substituted; but the great drawback to this lamp was its frailty, the breakage per day often averaging four per cent. of the total number of lamps in use on the cars. These lamps required about forty-five volts and one ampere of current, and each car contained ten lamps, seven in the body, one in the smoking-room and one in each vestibule, thus using about ten amperes of current; and as the batteries were rated at seventy ampere hours, we should have obtained from six and one-half to seven hours' good light, but it was very seldom, after the batteries had been used for a short time, that we could get over five and one-half hours'. As will readily be seen, this could hardly be called economical, for to obtain five or six hours' light we were obliged to charge from fifteen to twenty hours with a Brush arc light dynamo giving a current of about ten amperes. Then taking the weight into consideration, each time the car needed charging, the trays, six in number and weighing 1,200 pounds, had to be loaded on the truck, pulled over to one side of

the car, and the discharged trays taken out and the freshly charged ones put in their place. The remaining three were then taken around to the other side of the car and changed in the same manner. As the cars invariably stood on a double track, it was necessary to carry half the trays for some distance, over tracks, etc. Then, again, the tracks were usually full of cars, and if there was not sufficient time for them to be parted the batteries had either to be carried under the car or over the platform. Under the present system this has been done away with to a great extent, as will be explained subsequently. During the month of December, 1886, we commenced using one battery of the 7 B type, manufactured by the Electrical Accumulator Company. This battery was a decided improvement over those previously used, giving, as it did, nearly double the number of ampere-hours for the same weight of material. After using this battery for about a year, the positive plates began to give way, and new ones were substituted, the negatives, however, being retained, as they had not deteriorated. In fact, we are still using the negative plates of our original 7 B battery. This battery proved to be so satisfactory that in June, 1887, we added two more of the same type and two manufactured by the Julien Electric Company. The latter batteries were similar in size and shape to the 7 B type of the Accumulator Company, but did not seem to stand the hard usage so well, as they would crack instead of buckling and allow a large quantity of the paste to become loosened and fall out. It is proper to state, however, that these plates were made especially for us, to fit the cells we were using, and were not of the regular Julien type. This, no doubt, will account in a great measure for their failure to keep up to the standard of the present type of Julien batteries. After the positive plates of this battery became worthless, and not having any others to put in their place, we decided to make a kind of consolidated affair, and see how Julien negative and Accumulator positive plates would work together. The result was extremely satisfactory, and we have had no trouble with them whatever, excepting the occasional buckling of a positive plate.

During the fall of 1887 we began substituting the Accumulator batteries for the Brush batteries, and by the end of the year were using them altogether, with the exception of the two Julien I have mentioned. We, however, kept ninety-six of our best Brush cells, to be used in case of an accident to the incandescent

dynamos, which are used to supply the current for the railroad telegraph as well as for lighting the passenger station.

After the change in batteries had been made, it was thought best to change the system of wiring the cars, so that instead of its being necessary to put batteries on each side of the car, we need only put them on one side and get the same amount of light. This was done by connecting the two boxes under the car in parallel, and substituting 23-volt Edison lamps for our 45-volt Brush-Swan lamps. After doing this we found that we were able to get as many hours' light from twelve cells as we formerly did from twenty-four. Of course this change reduced the expense of lighting the cars considerably, for where we formerly had a change of battery for each car, or forty-eight cells, we now needed only twenty-four cells per car, with a few extra ones to be used in case the twelve cells would be unable to supply sufficient light for a long trip. This system of lighting proved so successful that it was decided to substitute it for gas in the remaining seven parlor cars. The wiring of these cars was commenced at the Meadow shops, near Jersey City, last September, and has just been completed. These cars are arranged for the 23 C type of the Accumulator Company's battery and 19 B type of the Julien battery. The battery boxes under the cars are larger than the old style, and contain four trays or sixteen cells, the lamps we used taking twenty-three volts of current. Changes were also made the first of the year in the system of charging, and the batteries are now charged from an incandescent dynamo instead of an arc, thus enabling the batteries to be charged with any amount of current desired. In connection with this description of the four years' work of the Pennsylvania Railroad, I would like to add something in regard to the electric lighting of the Chicago limited express.

In 1887 the Pullman Palace Car Company commenced using the electric light on one of three trains of the New York and Chicago limited express, and the charging of the batteries at Jersey City was given into the hands of the Pennsylvania Railroad Company. The batteries used were the 7 B type of the Electrical Accumulator Company, thirty cells to a car, and usually there are six cars in the train. These batteries would furnish enough light for one trip, and each time the train arrived at either terminus it was necessary to replace them with freshly charged cells. This was not objectionable at Chicago, for the

train arrived there in the morning, so that they could be charged during the day; but in Jersey City, where the train did not arrive until evening, the work was very difficult on account of the dynamo being in use for other purposes. After this one train had been running a short time, another one was fitted up, 19 B type of Julien battery being used. It was thought that this would give us a chance to see which was the better of the two batteries, but they both worked very well, considering the treatment they received. After Mr. Bauer became connected with the Pullman Company he did away with charging the batteries at the ends of the line, and introduced a Brotherhood engine and Eickemeyer dynamo in the baggage car of each train, in order that the batteries might be charged in transit. When the train leaves Jersey City the baggage car is on the rear, and consequently no charging is done until it leaves Philadelphia, where the train is reversed, bringing the baggage car next to the locomotive. The batteries are charged continuously until the train reaches Chicago, and the same practice is continued on the return trip. The steam for driving the Brotherhood engine is taken from the locomotive boiler, and the exhaust is used for heating the train.

So far as the Pennsylvania Railroad is concerned, the electric lighting of passenger trains may be considered an assured success, and leading, as it does, to the abolition of kerosene lamps, and incidentally encouraging the adoption of steam heating, the safety and comfort of the passengers are certainly increased.

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DISCUSSION.

Mr. Geo. B. Prescott, Jr.:—I think Mr. Brown's paper is very interesting, and I am sure the Pennsylvania Railroad Company deserves a great deal of credit for making the experiments. I think that these tests have demonstrated one thing very positively, and that is, that an accumulator made entirely on the Planté principle, without active material applied according to the Faure method, is an impracticable battery for commercial purposes. The improvement in storage batteries of late years, and particularly in the past year, has been very great, and the practical use of batteries shows that unless they are handled as if they were a delicate piece of machinery they will never give very satisfactory results. Wherever accumulators have been properly installed and have been treated as if they were worthy

of being properly cared for, they have been very reliable, and they certainly fulfil certain conditions that no other electrical machinery does to-day.

The improvements in the use of electrical accumulators are not confined to the cells themselves. No matter how good an accumulator may be, if it is not properly installed with suitable apparatus for regulating both the charge and discharge, it will never give satisfactory results. If the accumulator is overcharged, the paste is peroxidized to such a high degree that it becomes a very fine powder, without sufficient consistency to hold together, and it gradually deposits in the bottom of the jar. That comes from overcharging, and yet it was only a year ago that it was thought that overcharging improved accumulators. We know now also that if the cells are allowed to overdischarge they become very heavily sulphated, and the longer they stand in a discharged state the more dense this sulphate becomes, and then, if the charging is commenced at what would otherwise be the normal rate, the gas seems to be developed within the interstices of the pellets, and as the sulphate is not in a condition to take up the oxygen it is liberated, and the result is that these pellets are forced right off the perforations in chunks, so to speak. If, however, the cells are charged and discharged within certain limits, which can be determined for every size of cell, and if any short circuits that may occur through accident or other cause are removed at once, the accumulator, to-day, is a perfectly reliable piece of apparatus.

Mr. C. O. Mailloux:—I would like to ask Mr. Brown whether the charging of accumulators at either terminus of the road has been definitely abandoned in favor of the system of charging on the train. I ask this question because I know that on some roads there is a very great and decided objection to deriving the energy for charging the batteries from the locomotive; that is particularly the case with the Boston and Albany Railroad. I once had occasion to discuss the matter with the President of the Company, and he would not entertain at all any project for charging the batteries on the road, for the reason, he said, that they needed all the energy, whether they used it in the form of steam or derived it from the axle—they needed it all for propelling the train itself, their object being to make the shortest time.

I would like to ask another question about the latest modifica-

tions. Mr. Brown said that a smaller battery would do the work. I do not exactly understand this, unless he used lamps of higher efficiency, giving the same candle power with a smaller expenditure of energy. I would like to have him elucidate that matter for us.

Mr. Alex. S. Brown:—Mr. President, in regard to the charging of batteries on a car or at the terminus, you will understand that the Pennsylvania Railroad still charge at Jersey City. It was the Pullman Company I alluded to; they have done away altogether with the charging at either terminus, with the exception of keeping a few spare cells both at Jersey City and Chicago, so that in case the train arrives in Jersey City in the evening, and anything is the matter with the cells, or the trays, we simply have a good tray ready to put in its place.

In regard to the lamps. I spoke of using a battery with a less number of cells. When we were using 24 cells of the accumulator battery we would get about 14 or 15 hours' light, using the Brush-Swan lamps of 45 volts. When we changed and commenced using 23 or 24 volt lamps and 12 cells we got about 7 hours' light. You see it was really about the same thing, but we found it was easier to change the cars a little bit oftener and use a less number of trays, and at the same time we had to keep a less number of cells on hand in the battery-room. We found it more economical in both ways to work in that manner.

Mr. Wm. H. Peirce: I would like to ask the weight of those cells per lamp, and if there have ever been any experiments tending to show the quantity of steam used.

Mr. Brown: I really cannot say very much about the Pullman work, because I am not connected with that in any way now. I do not know just how much steam they require. But in regard to the other matter—the lamps—I supposed it to be a 16-candle power lamp; that is what they are held up to. Of course they may fall off a little, but when the battery is properly charged, they seem to hold right up. We have no method of testing in Jersey City, but that is what they are rated at. The weight of a cell is about 50 pounds.

Mr. Peirce:—That feeds how many lamps?

Mr. Brown:—We use 10 lamps on a car. The weight of battery on a car is 600 pounds; we use 12 cells.

Mr. Prescott:—Mr. Mailloux referred to the objection that he had heard made by some railroad company to making use of

steam for driving the dynamo. I think that objection is not very well founded. We all know that the use of steam for heating cars is being universally adopted, and some steam could be used for driving a small engine to run the dynamo and the exhaust used for heating the car. On the other hand, the amount of steam required to drive the small engine is such an almost infinitesimal part of the total amount of steam generated in a locomotive boiler that it hardly need be taken into account.

Prof. Edward L. Nichols:—I should like to inquire of the author of this paper whether he can tell us anything about the average life of accumulator cells used in railway service as compared with the life of the same type of cells doing the same amount of work when stationary. I have had this question asked me many times and have looked in vain for definite information concerning it.

Mr. Brown:—I am sorry that I cannot answer that question, because I have never had any experience with stationary cells. My experience has been confined entirely to railroad cells. We calculate our positive plates will last about a year. They are in use almost all the time. Of course they have a great deal more usage than the stationary cells, although I do not think that the motion of the train does them any harm at all. We do not find that the batteries splash any. Of course there is some little motion, but being in the center of cars about 65 feet in length, the motion there is very little, so I do not think that does any harm.

The President (Prof. Elihu Thomson):—Mr. Vansize can probably give us some information on the point just raised.

Mr. W. B. Vansize:—As to the President's suggestion, I would say that the details under consideration come more within the line of practical every day contact with the work, with which I have had very little experience. I have heard it suggested, however, that there might be some advantage in the motion on a railroad car, because the agitation of the liquid would make a more even dispersion; that is, the specific gravity would be more equal at all points of the cell, and while there might be some detrimental results from the shaking to which the material was subjected, the difficulty in that direction would be perhaps more than made up by the uniformity of the electrolyte. I do not know that any tests have ever been made to determine this question.

Prof. Nichols asked the relative duration of a cell whose life was spent upon a car as compared with that used in stationary work. I do not know that it has been determined; but the general opinion is, so far as my experience goes, that the railway cell has a somewhat abbreviated life. The varied attention which the two classes of cells receive would also determine that result to a certain extent. A cell in use on a railroad train would naturally receive a little more careful attention than a stationary cell, unless a system of inspection was in use in connection with the latter.

Mr. Mailloux:—I may be able to give some information in that direction by reference to the experience on street car lines. The storage battery is never put to a more crucial test than it undergoes upon a street car. My own experience and observation lead me to believe that a battery submitted to the same rates of charge and discharge would last longer on a car than in stationary places. I have seen the same battery when used in stationary work and when in use on street cars and also in railroad cars. In street cars the work was always necessarily much more severe. There were times when the battery might have to withstand a current rate of from 50 to 100 amperes; while in stationary work the same battery would never have a current rate exceeding perhaps 25 to 35 amperes; and yet, even under those very trying conditions, I have known of batteries, the positive plates of which were still quite good after fifteen months' use—almost daily use. For a long time the plates were used daily at least once, and sometimes charged twice a day, and yet after fifteen months' use the active matter was not sufficiently gone; in other words, the plates (of course I refer to the positive plates, because the negatives were nearly as good as ever) were still perfect enough to do good work, and this would show that there must be something in the vibration or the shaking of the cells which counterbalances somewhat the hard usage which it receives in the way of excessive rates of either charge or discharge. The particular battery which I refer to was once discharged on short circuit while on the road by the bursting of an armature. One of the cars was going down the steep grade in the upper part of Madison Avenue and the man thought it would be splendid fun to coast down hill. I suppose he must have developed a speed of 20 miles or more, and one of the armature bands ruptured, and being only a street car man he did not seem to think that that made much difference—perhaps

he did not notice it. When he got to the bottom of the grade he very innocently turned the switch to put on the current. The car did not seem to move very fast, and he was made conscious that something had happened by the conductor telling him that something was smoking. The trap door was removed, and he found that one of the motors seemed to be burned up. So the car was brought back. It was an experimental car, and upon investigation I found that the current rate of discharge had been sufficient to burn up one of the connecting strips by which the circuit was closed from cell to cell. In other words, one of these strips had acted as a fusible plug, and from its area of section I concluded that the current rate must have exceeded 300 or 400 amperes. I also found that the field wire, which was 4½ B. & S. gauge wire, had become heated sufficiently to char the insulation almost the whole length, so I concluded that it must have had a fair rate of discharge. I naturally thought that the batteries would be ruined, but I had them taken out and cleaned, and to my great surprise I found that while there was some active matter in the bottom of the cells, it was not at all, in quantity, what I expected. In fact, it was so little that I did not know how much of it was due to that immediate circumstance and how much was due to previous wear and tear. At any rate, the batteries were put into the same car, except two of them, which were ruined by the melted lead flowing out where the circuit was broken by the melting out of the safety plug. Shortly afterwards the same battery was again short-circuited by some accident which occurred in the station itself while making connection with the machinery. It was short-circuited in such a way that only the field wire of one of the motors was put across the terminals, and the connection seemed to be better this time, and we did not know of it until we heard a violent hissing noise. I jumped on the car—it was one o'clock at night—and struck a light, and noticed that the solution was boiling in several of the cells; so I very quickly opened the circuit and we found that the battery had been discharging at an excessive rate. Again I thought the cells might be ruined, but I had them washed and cleaned, and they did a good deal of work after that. This goes to show that in the first place storage batteries will stand a much higher rate than generally supposed, with comparative impunity, and it corroborates perhaps the belief which I have that when once the active matter of a storage battery has become thoroughly recep

tive by a proper course of treatment either originally in the making or construction of the battery or subsequently in the nursing or treatment of it, that you can do with it a great deal that would ordinarily be considered as abuse.

THE PRESIDENT:—As we have another paper on the storage battery, perhaps it would be well to have the paper read before continuing this discussion. We have with us Dr. Duncan and he will give us a paper on the inherent defects of lead storage batteries—a subject which cannot fail to be of great interest.

*A paper read before the American Institute of Electrical Engineers, New York, May 2nd, 1889, and discussion thereon.*

# THE INHERENT DEFECTS OF LEAD SECONDARY BATTERIES.

BY DR. LOUIS DUNCAN AND H. WIEGAND.

Since the year 1881, when the inventions of Faure gave such an impetus to the industrial development of lead secondary batteries, their commercial history has been marked by numerous and disastrous failures, while at the same time there has been a steady improvement in their construction and performance until at present they have reached a stage which makes them for some purposes a commercial success. At the same time there remain in the best batteries a number of defects which prevent their taking the place in the practical development of electricity which rightfully belongs to them. The action of the secondary battery is quite well understood. In the Faure type a support plate, usually made of lead or an alloy of lead, has mechanically applied to it some salt of lead (minium or litharge). A number of such plates are placed in dilute sulphuric acid, the alternate plates being connected respectively to the + and − poles of some source of electricity, and a current is sent between them. The result is a reduction on the positive plates (the plates through which the current enters) to $Pb. O_2$ on the negative plate to spongy lead. After this "formation" the action, roughly speaking, consists in a reduction of both peroxide and spongy lead to sulphate of lead on discharge, while on charging they are reduced again to their original composition. We find that in the process of charge and discharge there is a loss of energy varying from 15 to 40 per cent. within the practical limits of discharge rate. If we calculate the theoretical storage capacity of a given weight of lead and peroxide, we will find that the plates of even the best modern batteries weigh for the same capacity ten times as much as would those of a theoretically perfect cell. We will find, too, that there

is a constant depreciation, especially of the peroxide plates, the rate of depreciation increasing with the rate of discharge, and in general depending partly on the way in which the cell is treated, partly on its construction. The principal defects of the modern lead secondary battery are (1) the comparatively small storage capacity, (2) the loss of energy, (3) the depreciation, (4) the low discharge rate necessitated by considerations of efficiency and depreciation.

It was especially the question of the loss of energy in the battery that we wished first to investigate. There are two factors which determine the extent of this loss: in the first place, the number of ampere-hours obtained on the discharge of the cell is less than the number put in; and in the second place, the P. D. at the terminals is greater during charge than during discharge. This loss of energy exhibits itself in two ways—in a generation of heat, and in chemical actions which are not reversed on discharge. It is well known that after a cell has been in use for some time, especially if it be submitted to rapid charge and discharge, there will be found in the bottom of the containing vessel a white, powdery deposit, a sulphate of lead which has been formed from the active material of the plates and which has not been afterwards reversed. Again, when the cell is charged we find bubbles of gas escaping from the plates during almost the whole of the charge, the escape becoming quite violent towards the last. The escape is at first principally from the positive plate, but afterward it is from both plates. This escape represents, of course, a loss of energy due to the electrolysis of the di lute acid in the cell, the products being free hydrogen and oxygen.

Let us consider what takes place during the charge and discharge of a cell. Supposing the cell to have been discharged until its P. D. has dropped to 1.8 volts, on beginning to charge the P. D. increases until it reaches a value of about 2.1 volts—at a normal charge rate,—then increasing very slowly during a considerable portion of the charge, then increasing faster until it reaches a value of from 2.4 to 2.5 volts, when the cell is "boiling." The chemical action results principally in the reduction of the sulphate of lead on the two plates to peroxide and spongy lead respectively. The greater the charge rate the higher will be the P. D., and the sooner will the cell begin to boil, and the greater will be the loss.

On discharge the P. D. drops to from 2 to 1.95 volts for normal discharge rate, where it remains during the greater part of the discharge, there being a gradual fall during the latter part to 1.8 volts, when the discharge should cease If a high discharge rate be employed, there is a decrease in the capacity and efficiency, and a more rapid depreciation. If the discharge be continued after the P. D. has dropped below 1.8 volts, there will be a formation of white sulphate on the plates, there will be a loss of energy, as will be shown, and there will be a rapid depreciation of the cell. The result of the discharge is a formation of sulphate of lead on both positive and negative plates If we test the specific gravity of the solution at different times we will find that the solution has a maximum strength—say 1.200—when fully charged, with a minimum on discharge—say 1.150,—the sulphating of the lead decreasing the strength of the solution. The number of ampere-hours obtained on discharge is less than the number put in by an amount depending on the construction of the cell and the conditions of charge and discharge. There is a further apparent loss of energy in the fact that the electromotive force on discharge is less than that during charge.

Our first experiment was made to determine, if possible, whether part of this difference of E. M. F. was not due to the fact that the strength of the solution *in the plugs* varied, it being stronger during charge than during discharge. During discharge the sulphuric acid in the plugs has its strength decreased by the sulphating of the lead or peroxide. This weakening continues until the diffusion of the stronger acid in the cell produces a condition of equilibrium. It is known that the electromotive force of a cell varies with the strength of the solution, being higher as the strength increases. Gladstone and Tribe have found that when the acid is very weak the chemical action is changed, the result on a positive plate of sheet lead being the formation of streaks of a mixture of yellow and puce-colored oxides, while on other parts a white substance is formed, which is easily detached, falling in clouds into the liquid. This white substance is probably a basic sulphate of lead. When this action takes place the corrosion of the plate is more than doubled. So if the diffusion in the plug is slow, it may very well happen that there will be a great difference of density during charge and discharge, causing a difference in electromotive force and a formation on discharge of chemical compounds which are not afterwards reduced. A

rapid discharge rate would tend to greatly weaken the acid, and therefore to decrease the efficiency and hasten corrosion of the positive plate.

To find the rate of diffusion we soaked the plates or single plugs to be experimented on in acid of a specific gravity of 1.175, and then placed them in vessels of distilled water, letting them remain for different intervals of time, and determining the amount of acid diffused out into the water. To give some idea of the magnitude of the result, I select the following figures from a number of experiments. The plates used weighed about a pound and a half (.7 kilos.), and were of the grid type :—

POSITIVE PLATE.

| | CHARGED. | DISCHARGED. |
|---|---|---|
| Time in water. | Acid diffused. | Acid diffused. |
| 1 min. | .695 grms. | .29 grms. |
| 5 " | 1.41 " | .60 " |
| 30 " | 2.50 " | 1.43 " |

NEGATIVE PLATE.

| | CHARGED. | DISCHARGED. |
|---|---|---|
| Time. | Acid diffused. | Acid diffused. |
| 1 min. | .86 grms. | .317 grms. |
| 5 " | 1.42 " | .700 " |
| 30 " | 3.05 " | 1.35 " |

The curve shown in Fig. 1, gives the diffusion from a charged positive plate.

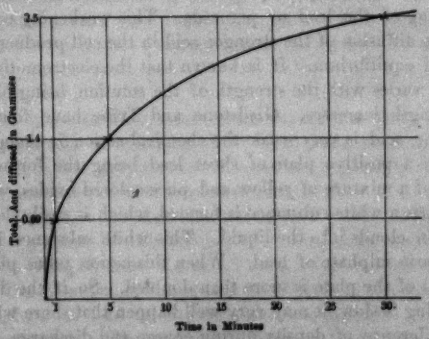


Fig. 1.

The total amount of acid in the charged positive plates was

(25 grms. of 1.175) about 5 grms.; so it will be seen that the rate of diffusion of the acid in the interior of the plugs is slow, for after 30 minutes, when half of the acid remains in the plug, the rate of diffusion has decreased from about .7 grammes for the first minute, to about .025 grammes per minute. While this is hardly the condition of affairs in actual practice where the rate at which the acid is being added or abstracted varies in different parts of the plug, yet it gives us some idea of the magnitude of the quantity. It should be noted that the rate of diffusion is materially the same for positive and negative plates, but that the rate for a discharged is considerably less than that for a charged plate. Keeping these facts in mind, let us pass to the phenomena of charge and discharge.

To investigate the loss of energy from heating, we placed the cell to be experimented on in a wooden box lined with a layer of felt about an inch thick. There was a top for the box, also lined with felt, and through it passed the rod of a stirring paddle and the stem of a thermometer. Experiments showed that the loss of temperature in this arrangement was, for a

| Difference between air and box. | Degrees loss per Degree diff. per hour. |
|---|---|
| 7.2° | .12° |
| 5.1 | .1 |
| 4.2 | .95 |

In the experiments we tried as nearly as possible to keep the air and cell at the same temperature, and the correction for radiation could usually be neglected. The cell was charged and discharged under a number of conditions, and the rise of temperature and other data were observed. The losses of energy that occur must, as has been stated, exhibit themselves in heat or in chemical changes which are not reversed. The cell was of the grid type, with 4 positive and 5 negative plates. The weights were:—

| | |
|---|---|
| Total weight | 25 lbs., 3 oz |
| Weight of plates | 17 " 8 " |
| " " vessel | 1 lb., 3 " |
| " " solution | 6 lbs., 8 " |

This gives a neat capacity for the cell such that the energy lost is approximately 3.2 watt-hours per degree.

The cell was first charged at 5 amperes until over 150 ampere-hours had been put in; both positive and negative plates were

boiling freely. The discharge was at a rate of about 15 amperes. Some of the particulars of the discharge are:—

| Ampere-hours discharge. | Rate of rise of temp. per amp.-hour. | Total rise of temp. | $C^2$ R. |
|---|---|---|---|
| 10 | .012 | .... | .... |
| 20 | .01 | .... | .... |
| 30 | .008 | .... | .... |
| 40 | .015 | .... | ... |
| 50 | .03 | .... | .... |
| 60 P. D. falling. | .05 | 2.03 | 11 watts. |
| 70 | .12 | .... | .... |
| 77 | .30 | 3 75 | 18 watts. |

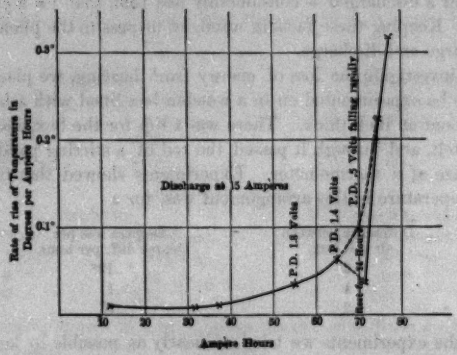


Fig. 2.

In this case the discharge was carried far beyond the limit of economical discharge. It will be seen that the loss is greater as the discharge continues, increasing slowly until the E. M. F. begins to drop, when it rises very rapidly.

After this discharge the cell was charged at a rate of 10 amperes.

RATE OF RISE.

| Ampere-hours. | Degrees. | Total rise. | $C^2$ R. |
|---|---|---|---|
| 20 | .04 | .... | .... |
| 40 | .04 | .... | .... |
| 60 | .05 | .... | .... |
| 80 | .08 | 4.7 | 8 |
| 100 | .166 | 8.9 | .... |
| 120 | .20 | 11.5 | 12 |

The cell thus charged was discharged at a rate of about 20

amperes. The rate of rise of temperature was very much as in the case of the discharge at 15 amperes. The total rise, with the P. D. down to 1.7 volts, 60 amperes having been taken out, was 1°.1; on further discharge down to .7 volts, taking about 20 ampere-hours more from the cell, the rise was 4.1°. This again shows that the loss increases as the P. D. falls.

The next charge was at 20 amperes. The rate of rise of temperature is given by the curve, Fig. 4. The total rise was 30.7°. The rise for 100 ampere-hours was 11.5°. The corresponding values of $C^2$ R. were 34 watts and 20 watts.

The effect of a rest is shown on the portion of the curve between 105 and 120 amperes, where a 16-hour rest gives a con-

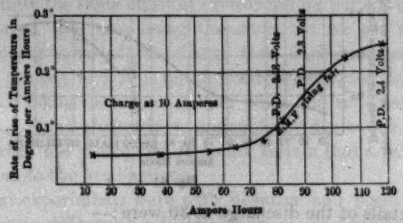


Fig. 3.

siderable reduction in the rate of temperature increase. The maximum rate is about .3 degrees per ampere-hour.

The cell thus charged was discharged at a rate of 30 amperes. The discharge was divided into periods of 20 minutes, with periods of equal length between, the object being to determine, if possible, whether there is a local action in the mass of the plug due to the different chemical conditions of the different parts of the plug, which would especially be the case if the charge or discharge were rapid. As in the previous case of discharge, the rise of temperature was slow, there being a gain of but 1.3° for a discharge of 40 ampere-hours, the heating effect of the current in that time being 12 watts, equivalent to almost 4°. For the first three periods there was little, if any, rise during the time of repose; for the fourth period there was a rise of about .1°, or .3 watt hours. During the fifth period the E. M. F. began to fall, and during repose after it the temperature rose .15°. The sixth discharge period was with the same current, but at a greatly reduced P. D. and resistance. It lasted 12 minutes; after it the temperature rose .5°, corresponding to 1.5

watt hours. The output of this discharge was 44 ampere-hours at a normal P. D.; 11 at a low P. D. The total rise of temperature was 3.5°; the value of $C^2$ R was 16 watts.

The cell was then charged with 70 ampere-hours at 30 amperes, the same period of repose being allowed. There was a definite rise amounting on the average to about .2°; after the first period the rise was but .1°, the others slightly over .2. The details of the charge were:—

| Ampere-hours | Rise in temp. | Rate. | $C^2$ R |
|---|---|---|---|
| 15 | 1. | .067 | 4.5 |
| 40 | 4.4 | .18 | 11.5 |
| 70 | 13.1 | .29 | 20.5 |

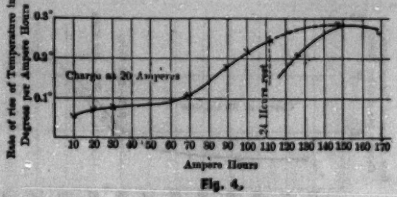


Fig. 4.

The details of the discharge at 30 were:—

| Ampere-hours. | Rise. | Rate. | $C^2$ R |
|---|---|---|---|
| 10 | .14 | .014 | 3.2 |
| 25 | .62 | .032 | 7.7 |
| 35 | 1.02 | .04 | 10.7 |
| 45 | 1.62 | .06 | 13.7 |
| 54 P. D. fell. | 2.62 | 1.1 | 16.5 |

The rise during the periods of rest for this discharge was at first small, but afterwards something over .2°.

The next charge was at a rate of 40 amperes. The following are the figures:—

| Ampere-hours. | Rise of temp. | Rate. | $C^2$ R. |
|---|---|---|---|
| 20 | 1.5 | .075 | 8. |
| 43 | 3.9 | .11 | 15. |
| 63 | 8.0 | .20 | 22. |
| 80 | 13.2 | .3 | 28. |
| 97 | 18.65 | .32 | 34. |
| | Rest. | | |
| 106 | 21.35 | .30 | 36.75 |

The rise during periods of repose was .1° for the first period, .7° for the second, and decreased as the charge increased until it reached a value of about .2°.

The discharge corresponding to this charge was also at 40 amperes, and was divided into periods as before.

| Ampere-hours. | Temp. | Rate. | $C^2 R$. |
|---|---|---|---|
| 14 | .46 | .033 | 5. |
| 28 | 1.16 | .05 | 11. |
| 42 | 2.24 | .077 | 17. |

Whether the rise in temperature during the periods of rest is due to the heat of the plates being diffused into the liquid, or is due to a local action in the plugs is difficult to determine. If it were due to local action we would expect a greater rise during the first periods of the charging experiments, and this is what we find. If it were due simply to diffusion of heat, we should have approximately the same effect at corresponding periods of charge and discharge, the rates being the same, but we see that it is greater during some of the charge than during corresponding discharge periods, and it is not uniform even during charge and discharge, it being sometimes greater when the resistance of the cell is less. Some of the rise is undoubtedly due to the diffusion of heat from the plates, but it seems certain that a part of the effect is due to the local action.

Our next experiments were with negative and positive plates which were in different conditions of charge and discharge. At first a cell was made up of fully charged negative plates, with positives from which 45 ampere-hours had been taken, and it was discharged in the calorimeter at 10 amperes.

| Ampere-hours. | Rise. | Rate. | $C^2 R$. |
|---|---|---|---|
| 4.2 | .05° | .012° | .5 |
| 17.5 | .20 | .011 | 1.8 |
| Rest. | | | |
| 35.8 | .45 | .009 | 2.6 |
| 49.1 | .85 | .03 | 4.0 |
| 66.1 P. D. fell. | 3.05 | .13 | 6.0 |

Next a cell with fully charged positives and negatives from which 47.5 ampere-hours had been taken, was discharged at a rate of 5 amperes.

| Ampere-hours. | Rise. | Rate. | $C^2 R$. |
|---|---|---|---|
| 10. | —.1° | —.01° | .5 |
| 15.5 | —.15 | —.01 | .75 |
| 20.5 | —.20 | —.01 | 1.00 |
| 23. | —.20 | —.00 | 1.1 |
| 29. | —.20 | —.00 | 1.4 |
| 34. | —.20 | | 1.65 |
| 39. | —.17 | +.008 | 1.9 |

| Ampere-hours. | Rise. | Rate. | $C^2$ R. |
|---|---|---|---|
| 41.5 | +.05 | +.08 | 2.05 |
| Rest. | | | |
| 47 5 | +.28 | +.04 | 2.45 |
| 49.5 P. D. fell. | +.50 | +.11 | 2.55 |
| Cell short-circuited, for very small current. | | | |
| 1 hour. | + .80 | | |
| 6 hours. | + 3.00 | | |
| 11 hours. | + 5.2 | | |
| 22 hours. | +11.2 | | |
| 23 hours. | +11.8 | | |

After this exhaustive discharge the cell was charged at five amperes, attempts at discharge being made at intervals. At first the P. D. fell at once on closing the discharge circuit, but after about 16 ampere-hours had been put in, a discharge of five amperes for eight minutes was obtained. The temperature, which had been rising quite fast, began to rise slowly at this point, the rates being given by the curve.

The cell boiled with a charge of 117 ampere-hours, when the total rise of temperature was 96°, $C^2$ R — 7 watts. For a charge of 160 ampere-hours the rise was 17.3° with $C^2$ R — 9 watts.

Another discharge of a negative cell which had 58 ampere-hours taken out gave :—

| Ampere hours. | Rise. | Rate. | $C^2$ R. |
|---|---|---|---|
| 9 | 0° | 0° | .5 |
| 22.2 | .39 | .019 | 2.0 |
| 31.0 P. D. fell. | .61 | .026 | 2.5 |
| 34.2 | .90 | .09 | 2.7 |

This gave the total capacity of the negative plates at a discharge rate of five amperes as about 90 ampere-hours; the previous experiment gave 93. The capacity of the positive plates was 94 ampere-hours. It was noticed in these experiments that when a partly run-down negative was used, the fall of potential after a value of 1.5 volts was reached, was very rapid. From 1.3 to .5 volts took less than a minute, while in another minute the value had reached .25 volts, and it was soon only a few hundredths of a volt. With the discharged positive, on the contrary, the fall was slow. After a value of 1.35 was reached, the fall in a half-hour was only to 1.04 volts, and in four hours it was .66 volts. After several hours short circuit, when the value had reached a few hundredths, the circuit was broken. In five hours the value was 1.65, and the next day it was 2.02 volts.

With some plates made by depositing thin layers of spongy lead and peroxide on lead support plates, the effect was still more marked. Here the P. D. of a negative plate fell from a value of 1.8 to .05 in ten seconds; while with the positive the fall was gradual.

Now let us see what our experiments, as far as we have carried them out, show. In the first place the loss that exhibits itself in heating increases as the charge or discharge goes on, not being very great in the latter operation until the P. D. has begun to fall. The loss is greater during charge than during discharge. For instance, take a discharge at 15 amperes, the P. D. begins to fall when 60 ampere-hours have been taken out. The total rise in temperature is 2.03 degrees, while the rise due to the heating of the current alone, ($C^2$ R) should be 3.4°. In other words, there has been an absolute lowering of the temperature by all the other actions outside of the Joule effect. Taking a

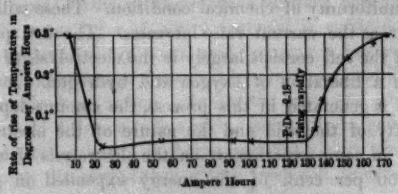


Fig. 5.

charge at 10 amperes, the rise for a charge of 100 ampere-hours was 8.9°, with a loss due to the Joule effect corresponding to 3°, a difference of 5.9°. The difference in the losses for charge and discharge—neglecting $C^2$ R—is about 5.3°. For a charge of 120 ampere-hours, the rise was 11.15°.

We will find the same results in all of the other records, there being sometimes an absolute fall of temperature on discharge. This is without doubt due to the fact that the acid is strengthened on charge, weakened on discharge. In changing from a specific gravity of 1.14 to 1.18, the evolution of heat is such as to raise the temperature of the solution about 3.2; there will be a corresponding cooling effect on discharge.

To the above charge, at 10 amperes there was a discharge at 20 amperes, which gave a total of 84 ampere-hours, of which 60 were at normal P. D.; the rise for normal P. D. was 2°; the total rise was 4.7°. $C^2$ R — 12.1 watt-hours for the 60 ampere-

hours at normal P. D., corresponding to 3 8°; the total value of $C^2 R$ for the 84 ampere-hours was 15.1, corresponding to 4.7°. The total heat loss in the process of charge and discharge was $11.5 + 4.7 = 16.2°$, or about 51 watts. The total loss obtained from taking the difference between charge and discharge energies, calculated from the ampere-hours and potential difference, was 98 watts, more than half of which appeared as heat. Of the 51 watts which appeared as heat, 27 were due to the Joule effect, 24 to other causes. We believe that part of this loss—a very small part—is due to local action between the positive material and the support plate. Another part is due to local currents in the plugs themselves. When the plate is charging or discharging, the distribution of current in the plug is not uniform, but it is denser at the surface than in the interior. After a while the plug is not uniform in its chemical composition, and there are doubtless eddy currents in such a way as to tend to bring the plug to uniformity of chemical condition. These will be more important as the current rate increases. The last part of the charge of the cell consists largely in the electrolysis of the dilute acid with a liberation of oxygen and hydrogen. It is known that heat is generated in this process, the amount depending on the density of the acid and the nature of the electrodes. M. Gramme in some experiments on the electrolysis of water, only utilized 50 per cent. of the energy expended in producing electrolysis, the remainder being lost. In our own case, when the charge has reached such a point that the reduction of the plates is complete, and the principal action is the electrolysis of the solution into free hydrogen and oxygen; if the total P. D. is 2.5 volts, and if the energy of combination of oxygen and hydrogen corresponds to about 1.5 volts, we may expect of the energy of 2.5 watt hours, corresponding to a charge of 1 ampere-hour, 1 watt-hour to appear as heat. If we look at the tables, we will see that the rate of rise of temperature for overcharge is in the neighborhood of .3° per hour per ampere, and this corresponds to about 1 watt, as we would expect. As this action (shown by the evolution of gas from the plates) continues through the whole of charge and part of the discharge (doubtless due to local action in the latter case); we will always have *some* corresponding rise of temperature, although it will not reach its full value until the cell is boiling.

The rise of temperature then, is due to:

(1.) The Joule effect, 27 out of 51 in this case.

(2.) Currents caused by local action between active material and support.

(3.) Currents caused by local action in plugs.

(4.) Heat losses corresponding to electrolysis of solution into free oxygen and hydrogen.

The last three probably account for the remaining 24 watts.

But there are 47 watts left unaccounted for, which must be due to chemical changes not reversed. The most important of these, *as far as loss of energy is concerned*, is doubtless the formation of free hydrogen and oxygen. Another component of the 47 watts is due to the local action between the plugs and support. But we believe the most important, as far as *deterioration* is concerned, is in the formation of irreversible compounds caused by the weakening of the acid in the plugs. We have found that the rate of diffusion in the plug is comparatively slow, so that during a rapid discharge there must be weak acid in the plug. Where the outer layer of active material is reduced, the inner layer is surrounded by weak acid, causing a lowering of the E. M. F. and corrosion, as described by Gladstone and Tribe, with a considerable local action between the outer and inner layers. As the rate of diffusion is less with a partly discharged than with a charged plate, a heavy discharge rate has a more marked effect with a partly discharged than with a fresh cell, as experience has shown.

These are, we believe, the principal sources of loss in a lead secondary battery, and the depreciation can be mainly charged to them. The expansion and contraction of the plugs in a grid plate is another source of trouble, and cannot be avoided. Our own experience has been that the losses are less with plane plates, coated with thin layers of active material, than with plates made of the grid form. Under any circumstances, an increase of surface for a given current rate is to be desired, as it lengthens the time of charge before the violent boiling occurs. A plane plate gives a uniform distribution of current, and, therefore, very little local action.

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DISCUSSION.

THE PRESIDENT:—I am sure we have all listened with great attention to Dr. Duncan's paper, as it brings forth a number of points which I do not think have been given the prominence

which they deserve, in relation to the storage battery, particularly the point of the existence of eddy currents due to the difference of chemical conditions of different parts of the plug; it also fixes the losses just where we would naturally expect to find them. There is one point I might simply ask information on. I understood the Doctor to say that there was a continual and rather large loss after the charging was completed.

Dr. Louis Duncan:—Not after the charge is completed and the current shut off, but when the action is simply the electrolysis of the solution.

The President:—I wish to offer one more remark—that possibly part of the loss may come in the recombination of the ozonized oxygen with the free hydrogen, producing heat in the solution itself.

The paper is open to discussion and we should be pleased to hear from any members on any of the points touched upon.

Prof. E P. Roberts:—I would ask if it was a constant rate of charge, or if the charge gradually tapered off as the battery filled. I was not quite sure when Dr. Duncan spoke of plates that merely had a face action instead of plugs, whether they heated comparatively more or less than when there was plug action.

The President:—I understand the inquiry to be whether there was more or less energy in the flat plate with the coating of active material laid over it than when the plugs were used? Is that it?

Prof. Roberts:—Yes, sir.

Dr. Duncan:—Well, the discharge and charge rates were always the same. As for the flat plates, I experimented on some plates which were made by depositing low and pure oxide on plane sheets of lead from a caustic solution of litharge. In that case with a very thin layer, about a quarter of an ounce to the square foot of spongy lead and a corresponding amount of peroxide, the efficiency of the cell at a discharge rate which corresponded to that of the Julien cell, 25 amperes for a surface of about 7 feet, I think, was about 90 per cent. But, of course, in that case the proportion of active material to total weight was very great. There was only a very thin layer and the distribution of chemical action was uniform and there was comparatively very little loss. A part of that could be accounted for by the electrolysis of water.

As for the heating effect due to the electrolysis, I think Prof. Thomson's suggestion is a very good one, but we did not attempt to find out what that heating effect was due to. It ought to be in about the same proportion, if the electromotive force is $2\frac{1}{3}$ volts, then for one ampere hour the loss is $2\frac{1}{3}$ watt hours. If the electrolysis itself takes up $1\frac{1}{2}$ of the $2\frac{1}{3}$ volts, then the other actions, whatever they might be, should give a loss of 1 watt hour. I simply put that $1\frac{1}{2}$ down to loss from heating effect. But it is probably due to the cause that Prof. Thomson gave.

Prof. Roberts:—I asked that because of an impression I got from some experiments, though I did not make enough of them to be sure it was the fact. I also happened to think of the practical bearing of the fact of the electromotive force rising after a few moments of rest. I happened at one time to have some storage batteries in my hands and the lights would get very bad at night, and the next morning it was a very nice thing, when the customer complained, to turn the light on and say, "See, the lights are all right and up to full candle power."

Mr. Townsend Wolcott:—I understand Dr. Duncan to say that the chemical action of the plug begins at the surface of the plate.

Dr. Duncan:—I think it does, yes.

Mr. Wolcott:—As far as my experience goes, if you take the ordinary form of plug, (Fig. 6.) the grid is so much better a

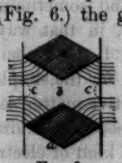


Fig. 6.

conductor than the active material that the latter starts to form right around the edge, and the last place that it is formed is right there in the middle. The thing is to get that middle formed up as good as the other part. I think that is where a good deal of loss comes in.

Dr. Duncan:—That probably is where that action does take place.

The President:—On the point just mentioned it would, of course, appear that that plug is not as good a conductor as it ought to be. If it were a very good conductor, then we would have it even up at once, even though it might not take place from actual conduction of the current to the plug.

MR. WOLCOTT:—That emphasizes the point that Dr. Duncan mentioned about a very thin film uniformly spread on a flat plate—that the action is equal all over. Of course, the current would come right straight out. There would be no spots.

MR. MAILLOUX:—There is one point regarding the rate at which batteries charge and discharge, which I think has a great deal of influence on the efficiency, and it also has some interest industrially. In order to get the most of a storage battery we want to charge it at such a rate that we should get the maximum efficiency, so as to lose as little energy as possible in electrolysis. On the other hand, the circumstances of its use dictate that the time expended in charging the battery should be as small as possible. Now, I think that it is possible to satisfy both requirements, because I have found by experience that a battery will stand during the first period of charge a very high rate without evolution of gas, and, if watched, it is possible to charge the battery in the minimum time, and also, probably, with as good efficiency as in any other way, by always keeping the current at such a rate that it will be just below the point where it causes evolution of gas. I have in this way made it a practice to begin charging batteries whose normal rate of charge would be say 15 amperes with as high current as 50 amperes, which could be kept up for an hour or two. Then, perhaps, 30 for another hour; then 20, then 10, then 5, and sometimes I would finish with as low as 3 amperes. Now, in that way the battery was never allowed to evolve gas, and I think that that is the best way in which to treat the battery, for the simple reason that it gives the energy as fast as the receptive matter can receive it. In charging, the surface probably becomes oxidized first, and the inside may become oxidized by a kind of electrolytic conduction in the plug itself, and you must give it time for the actions to take place, and by pursuing such a method you allow the necessary time, and do not evolve the gases. The condition which Mr. Prescott has called to our attention is a well known one—namely, the continued evolution of oxygen on a peroxide plate, after the battery is charged, disintegrates the active matter and makes the peroxide into a fine granulated form, which is not coherent, so that it is very undesirable to prolong the evolution of gas. On the other hand it is desirable to charge the battery fully. There is no way of doing it satisfactorily but by reducing the rate of charge towards the close of the charge.

Mr. Prescott:—I would like to ask Dr. Duncan if he took into account the difference in the internal resistance of the cells owing to the different state of charge or discharge in order to calculate the dual effect, and whether he took a mean of a few extreme readings or whether it was determined at uniform intervals.

Dr. Duncan:—It was determined every five or six minutes and the effect was calculated at corresponding times. The resistance for full discharge was sometimes five times as great as it was for full charge.

Prof. Nichols:—I wish to emphasize what seems to me the importance of the point brought out by Mr. Mailloux a moment ago, and the importance of the experiment Dr. Duncan has described. It seems to me that this is the only way in which this great number of perplexing questions that have arisen can be satisfactorily answered, and I think the sort of experiments described in this paper, made patiently and persistently, will finally give us complete control of this matter. This question of time is, of course, a very important one in the matter of charging. It would seem perfectly practicable to determine a rate to give the proper charge in the minimum time, never at any time giving it more than it can safely take, so as to complete the charge in the smallest possible interval. However, I think that this has more to do with the economic question of the time of charging than it has to do with the efficiency, and I think so, because in some recent tests which we have been making, they were really practice tests, but they brought out this point very nicely; the battery was charged first with uniform current throughout, at a rate not such as to produce marked evolution, then discharged and its efficiency determined. The same battery was then charged with a tapering current, starting off with a large amount and making the average current for the whole time of charging the same as before. The efficiency was found to be within one per cent. of what it was before. Finally the same battery was taken again and charged intermittently with uniform current and then breaking and allowing it to stand for half an hour, the impression being that there might be a reversible reaction which would take place if the battery had an opportunity to readjust itself between these charging periods. The battery was brought to the same condition and again discharged continuously, and all three of these efficiencies came out within one or two per cent. of each other.

Mr. Francis B. Crocker:—I would like to ask Dr. Duncan if the loss of energy by the evolution of gas could not easily be determined by collecting it. He refers to it as an unknown factor in the loss of energy. It seems to me the number of unknown factors could be reduced by determining the amount of energy the gases represent. The point which the President brought out in regard to the recombination of the oxygen and hydrogen would be eliminated also, because the gases collected would represent the actual loss of energy from the evolution, whereas the recombination would be heat, added to that produced in the battery. It seems as if one of the rather numerous factors of loss could be fixed in that way.

Dr. Duncan:—I think I was misunderstood if it was supposed that I said that the loss due to electrolysis of the solution was not a definite quantity. When you electrolyze a solution of sulphuric acid you get a definite amount of oxygen and hydrogen. That has been done by Gladstone and Tribe, and they find that it is a definite amount. But accompanying that is another loss. Gramme found that in electrolyzing dilute acid, the efficiency of the process was not much more than 60 per cent. under the most favorable conditions. It is not the loss due to electrolysis that is at all questionable. There is a heating which goes on entirely independent of the $C^2$ R effect, and what that heating is, I don't know. Probably what Prof. Thomson suggests will account for some of it. I do not think it would account for all, because most of the calculated amount of gas was collected by Gladstone and Tribe in their experiments.

Mr. Mailloux:—I think that in considering the work lost in electrolysis we must allow for the amount of heat which must be abstracted from the surrounding medium by the expansion of the gas. We must remember that as it is evolved into a gaseous form it expands, and in doing so it would necessarily absorb energy from surrounding substances, and as this energy must be provided by the circuit itself, it would probably react on the circuit in such a way as to cause either an increase of resistance or of counter-electromotive force. There are only two ways in which energy can be abstracted from the circuit, just as in the case of a transformer or dynamo; either by inductive resistance, in the form of counter-electromotive force or by ohmic resistance. I might point out that the very able and interesting researches of

Dr. Duncan will greatly facilitate the mathematical treatment of the storage battery, which thus far has been waiting for just such researches. If we consider the storage battery as a transformer, it is very easy to point out its analogy to other forms of transformers, and while generalizations are not correct, absolutely, to their full limits, yet there are a great many important points of resemblance. For instance, the induced currents and the local actions which Dr. Duncan has described, are very closely analogous to the currents of self-induction, while the losses due to heat, for instance, are analogous to the increased resistance due to heat and the consequent loss, and I think that before long somebody will give us analyses of the principles governing the action of a secondary battery, with as much clearness and exhaustiveness as we have had in the case of the dynamo or of the transformer

Mr. Prescott:—There is one point that I consider of very great importance which Dr. Duncan has passed an opinion on, to the effect that the active material applied to the surface of the plate produces better effects than when applied to a perforated grid. I should like to ask him what he considers the surface of the plate. Is it the surface exposed to the acid or is it the surface of the oxide in contact with the lead? Mr. Wolcott has made a diagram on the board, which shows that the most effective surface is that in contact with the metal itself, and if that is true, why, I should think the objection to the grid form would fail.

Dr. Duncan:—While action takes place all along the grid, yet if the diffusion is not very rapid the action at one point is taking place in comparatively strong acid, and the action at another point is taking place in comparatively weak acid. At the same time the condition of those points is different, therefore the loss will be different. With two plane sheets, one opposite the other, then the density would be exactly uniform, supposing the conductivity of the support were great enough. As far as the efficiency goes, the only experiments I have made, as I have stated, were with the deposit of peroxide upon plane lead plates from a solution of litharge caustic. If you take a very concentrated solution of caustic soda and potash and put in litharge, and boil it, you get on the lead plate a deposit of spongy lead, which will be a half inch thick for one quarter of an ounce. Then you can press that until it is about one-hundredth of an inch thick. You get about six-tenths of the theoretical capacity of the lead when it is compressed with a pretty fair pressure.

And it was with such plates that I got a higher efficiency than I did with grid plates, because their action is perfectly uniform and the thickness is so small that there is hardly any chance of eddy currents.

MR. PRESCOTT:—Therefore it is possible that the same method of preparing the plate if applied to the grid might have given the same result.

DR. DUNCAN:—The great point is that every part of the plate is in exactly the same condition. The distance from the other plate is exactly the same. Whereas in the grid plate there is a very great difference, and consequently the distribution of current is not the same.

MR. PRESCOTT:—The modern practice is to increase the separation of the plate very much more than has ever been done in the past, and also to make much thicker plates and to make smaller perforations. The result is that the difference in the distance between one plate and any portion of the interior of the perforation of the opposing plate is almost inappreciable. That is the modern tendency.

*A paper read before the American Institute of Electrical Engineers, New York, May 22d, 1889, with discussion thereon.*

# ELECTRIC MOTOR REGULATION.

BY FRANCIS B. CROCKER.

Although this subject is one of great scientific and practical interest, it has not been very frequently or very fully treated up to the present time. Of course, motor regulation is very similar to dynamo regulation, but it is by no means identical with it, and it deserves and requires separate treatment. I do not think it is much exaggeration to say that at the present time there is no subject more generally important to electrical engineers than motor regulation. Considering this fact, it is certainly remarkable that the literature of the subject is so limited. We find stray articles in electrical periodicals, rarely more than a description of one particular invention, and in electrical books, regulation is referred to incidentally in descriptions of the various motors. There is, also, to be sure, usually one short chapter devoted to this subject, but it is apt to be either very general, merely mentioning a few regulating devices, or else, it is confined to the mathemathical analysis of some one particular method.

Motor regulation is a subject which is somewhat confusing, and requires, therefore, accurate definition of the quantities and conditions which enter into it. One case is, at first sight, very similar to another, and yet more careful consideration will show, very likely, that it is exactly opposite. Take, for example, the two commonest and most important cases, viz: the constant potential and the constant current motors. The conditions of the two cases are precisely opposite and the solution of the problem is, naturally, entirely different. To maintain a motor at a constant speed with a variable load on a constant potential circuit, which is the case of the ordinary shunt motor on the regular 110 volt incandescent circuit, is a very easy problem; in fact, it solves itself. A simple shunt-wound motor will run at a practically con-

stant speed on a constant potential circuit, even if the load varies from zero up to the full capacity of the motor. Now this form of motor is exactly what we would use, even if we did not care to have it regulate.

It is customary, to be sure, where very close regulation is required, to wind constant potential motors differentially, *i. e.*, with series as well as shunt coils, but this is not essential for ordinary work. The case of the constant current motor, on the other hand, is as difficult as the first is easy. It seems as if it had to bear the burden of both. Neither a shunt-wound nor a series-wound nor a compound-wound motor can be used practically on a constant current circuit to maintain a constant speed with variable load. The ordinary series-wound motor, which is the natural and common form for the constant current motor, will race away when the load is taken off and increase in speed until it tears apart or strains the armature and ruins the machine. We require some special and very effective device to accomplish the regulation in this constant current case, and it seems to happen that almost every device that had been thought of has had serious difficulties and complications. The ordinary, and what would seem to be the best solution of this problem is to vary the magnetic effect of the field upon the armature directly in proportion to variations in the load. This is effected by cutting out the field coils, and by other methods which will be described later. But there are serious difficulties with almost all these plans.

These two cases, which, as already stated, are the commonest and most important which occur, and yet which are so very different in almost every respect, give a general idea of what we have to deal with in motor regulation.

In order to fix and hold the rather numerous quantities and conditions that present themselves in connection with motor regulation a tabular statement of them is given below.

TABLE I.

ELECTRIC MOTOR REGULATION.

1. Hand regulation.
   Usually employed for varying the speed.
2. Automatic regulation.
   Usually employed to maintain constant speed, and is effected by
   Centrifugal governors,

Dynamometric governors,
Electro-magnetic devices.

PRINCIPAL METHODS OF MOTOR REGULATION.

1. Shunt winding. (Fig. 1.)
2. Differential winding. (Fig. 2.)

Varying external resistance in series with

3. Armature.
4. Field. (Fig. 1.)
5. Both armature and field.

Varying internal resistance of

6. Armature.
7. Field by cutting out coils in series. (Fig. 3.)
8. Field by cutting out coils in multiple arc. (Fig. 4.)
9. Field by grouping coils in series or multiple arc.
10. Both armature and field. (Fig. 5.)

Varying shunt in multiple arc with

11. Armature.
12. Field.
13. Both armature and field. (Fig. 6.)

14. Varying current in separately excited field.
15. Shunting field magnetism. (Fig. 7.)
16. Short circuiting field magnetism. (Fig. 8.)

Varying commutation by

17. Shifting brushes. (Fig. 9.)
18. Shifting commutator.
19. Shifting magnetic resultant.

20. Moving pole-pieces away from armature. (Fig. 10.)
21. Moving armature away from pole-pieces. (Fig. 11.)

## Table II.

LIST OF POSSIBLE CASES WITH DIRECT CURRENTS.

$P$ = Difference of potential in volts at terminals of motor.
$C$ = Current in amperes supplied to motor.
$S$ = Speed of armature in revolutions per minute.
$L$ = Load or torque in lbs. at one foot radius.

Any of these four quantities may be either constant or variable, making the following combinations:—

| Case. | Constant. | Variable. | Example. |
|---|---|---|---|
| 1. | *P* | *CSL* | Series wound motor with variable load on constant potential circuit. |
| 2. | *PS* | *CL* | Shunt or comp. wound motor with variable load on con. pot. cir. |
| 3. | *PL* | *CS* | Shunt motor with con. load and var field resist. on con. pot. cir. |
| 4. | *PSL* | *C* | Not practical. |
| 5. | *PC* | *SL* | Not likely to occur. |
| 6. | *PCS* | *L* | Not practical. |
| 7. | *PCL* | *S* | Not practical. |
| 8. | *PCSL* | | Shunt motor with constant load on constant potential circuit. |
| 9. | *C* | *PSL* | Shunt motor with variable load on constant current circuit. |
| 10. | *CS* | *PL* | Series motor with speed gov. and var. load on const. current circuit. |
| 11. | *CL* | *PS* | Not likely to occur. |
| 12. | *CSL* | *P* | Not practical. |
| 13. | *S* | *PCL* | Motor with speed governor and var. load on cir. of var. pot. and cur. |
| 14. | *SL* | *PC* | Motor with const. load and speed gov. on cir. of var. pot. and cur. |
| 15. | *L* | *PCS* | Motor with con. load without speed gov. on cir. of var. pot. and cur. |
| 16. | | *PCSL* | Motor with var. load without speed gov. on cir. of var. pot. and cur. |

In Table i, motor regulation is divided into hand regulation, which it happens, is almost always used for varying the speed of a motor, by a hand switch, Fig. 1, for example; and automatic regulation, which is almost always used to maintain a constant speed, and which is usually accomplished in one of the three following ways: first, by a centrifugal governor similar to that of the steam engine, operating a switch or other device (Fig. 3); secondly, by a dynamometric governor, *i. e.*, a mechanism through which the load or torque of the motor is transmitted, which may also operate a switch and vary the power of the field by the direct

effect of changes in the load; thirdly, by an electro-magnetic device, such as a solenoid, through which the current or a portion of it, is passed, which causes the core of the solenoid to move and operate a switch, in accordance with variations in the current. (Fig. 9.)

The table next gives the principal methods used to regulate motors. These consist of different arrangements and combinations of parts, to produce different effects or changes in the working of the motor, and they constitute the means which we have to employ to accomplish a certain object in motor regulation. Method 1, is simple shunt winding, which consists in exciting the field magnet with a circuit of comparatively high resistance in multiple arc with the armature. (Fig. 1.) This maintains a motor at constant speed with varying load on a constant potential circuit, and does this all by itself, as it were, without any trouble, as already pointed out. The reason for this is, that the field, being fed with a constant potential, is, therefore, of constant strength, and a slight variation in speed of the armature, about five per cent., will vary the current in it from zero up to its full capacity, and, therefore, vary its power to an equal extent.

Method 2 is differential winding (Fig. 2), which is a refinement of the first, by which an almost absolutely constant speed, *i. e.*,

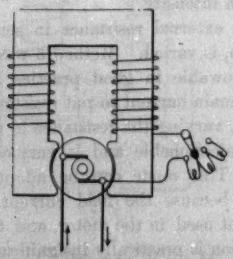

FIG. 1.—Shunt Motor with Variable Resistance in Field Circuit.

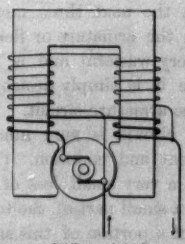

FIG. 2.—Differential Motor. Self-Regulating.

within one or two per cent., may be practically maintained. This consists in winding a series coil of comparatively few turns upon the field magnets, in addition to the shunt-winding in the previous case, the series coil being wound in the opposite direction and opposed magnetically to the shunt coil. The effect of this is to slightly weaken the field magnetism as the load on the armature,

and consequently its current increases. This tends to increase the speed of the armature and counteract its tendency to slow down with increased load, thereby almost entirely eliminating even the small variation of five per cent. in speed which occurs in the ordinary shunt motor. The paradoxical fact that a shunt

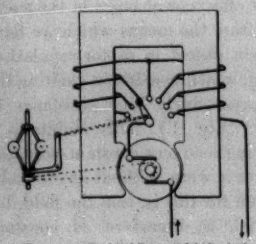

FIG. 3.—Series Motor with Switch for Cutting Out Coils in Series.

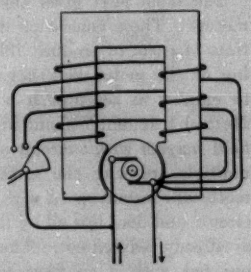

FIG. 4.—Shunt Motor with Switch for Cutting out Field Coils in Multiple Arc.

motor increases its speed with the weakening of the field magnet is well known, being due to the lowering of the counter-eletromotive force, and consequent increase of current in the armature as the field magnetism is reduced in intensity.

In the next three methods the external resistance in series with the armature or field, or both, is varied. Method 3 would be very wasteful and is hardly allowable in good practice, because it is simply destroying the main current to put resistance in the armature circuit. Method 4, varying the resistance in the field circuit, is very much less objectionable and is very convenient and common. (Fig. 3.) This mode can be adopted with a very small loss of current, because the field current is only a small part of the total current used in the motor, and the loss of a portion of this small fraction is practically insignificant. Method 5, putting external resistance in series with both the armature and field, is open to same objection as case 3, since it throttles and destroys part of the main current.

The next five modes of regulation, 6, 7, 8, 9 and 10, are theoretically more economical than the preceding, because we vary the internal or useful resistance, instead of adding external or dead resistance. Method 6, in which the internal resistance of the armature is varied, is very difficult to carry out in practice,

simply because it is hard to get at and change the connections of the armature while it is revolving. One of the few ways devised to accomplish this, is to wind the armature with two or more circuits connected to a corresponding number of commutators, whereby one or more of these circuits may be used, thus varying the internal resistance and torque. This is clumsy and is practically little better than using two or more separate motors.

Method 7, cutting out the field coils in series, is a very simple and common plan. It is the ordinary way of regulating constant current or other series-wound motors. This method, or some modification of it, is one according to which the constant current or "arc" motors of the Baxter, "C. & C." and Excelsior companies are constructed.

Method 8, of cutting out field coils in multiple arc, is shown in Fig. 4, and is especially applicable to shunt-wound motors. The different layers, for example, may be respectively connected to the contact points of a switch, and thrown into circuit successively, the innermost layer first, etc, thus obtaining the most economical result.

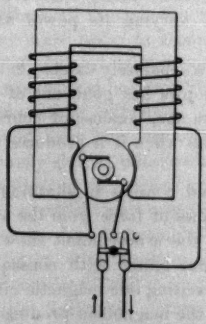

FIG. 5.—Motor with Switch for Throwing Armature and Field in Series or in Multiple Arc.

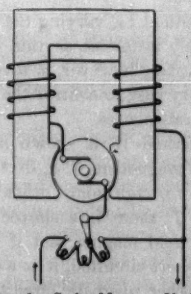

FIG. 6.—Series Motor on Variable Shunt.

Method 9, of grouping the field coils in series or in multiple arc, produces very great variations in field resistance, and is a combination of the two preceding cases. Like them, it consists in winding the field with separate circuits which are connected to a switch. This has been employed in street car motors to obtain great variations in resistance and power.

Method 10 is also merely a combination of two or more of the four preceding cases. A simple way of carrying it out is illustrated in Fig. 5, and consists in connecting the armature and field either in series or in multiple arc, by which a great variation in the total internal resistance of the machine is obtained.

The next method, No. 11, is open to the same objection as No. 6, because when the armature is shunted the main current of the machine is affected. This is, however, less objectionable than dead resistance, because in most cases, it is better to divert the current than to destroy it.

Method 12, like methods 4 and 7, is a useful and common one, because in shunting the field we are merely handling a very small fraction of the total current.

Method 13, varying a shunt in multiple arc with both armature and field, is wasteful, like No. 11. It was, however, the plan by which the first arc motors were regulated, a variable shunt being placed in the main circuit and the motor connected to the terminals of the shunt.

The variations in the shunt, of course, throw more or less current through the motor, thereby varying its power as required.

Method 14, varying the current in a separately excited field, is merely historical, as this class of motors has gone out of use. The plan, however, is a very effective one, because, of course, it is very easy to control the field current when it is produced by a separate source.

Method 15 is shown in Fig. 7, and consists in shunting the field magnetism, *i. e.*, diverting the lines of force from the armature through some other path. In the arrangement shown in Fig. 7, there is a simple series-wound motor with consequent pole field magnet, and if the coils exciting one magnetic circuit are short circuited, it is evident that the magnetism produced by the other magnetic circuit will be short-circuited or shunted by the former. The short-circuiting of the coils is effected by the variable shunt, as indicated.

Method 16 is very similar to the preceding, and consists in short-circuiting the field magnetism and diverting it from the armature by a keeper, which may be moved towards or away from the pole-pieces by means of a screw or other contrivance.

We now come to methods 17, 18 and 19, in which the line of commutation is varied. The first is the well-known plan of

shifting the brushes. This is very effective and easily carried out, and has, therefore, been used quite extensively; but it has the very serious and almost prohibitory objection that when the brushes are moved from the neutral point they spark very badly. This may be remedied to a slight extent by some heroic plan like blowing out the spark produced. But, as sparking is one of the worst drawbacks of a motor, it hardly seems as if this method of regulation would be permanent.

Method 18, shifting the commutator, is simply another way of doing the same thing.

Method 19, shifting the magnetic resultant or direction of lines of force in the armature, may be accomplished by two sets of pole-pieces, the relative magnetic strength of which is varied. This is also open to the same objection as shifting the brushes.

Method 20, shown in Fig. 10, consisting in moving or separating the pole-pieces from the armature, has been used in the Diehl and other motors, but it is rather difficult to carry out mechanically, and introduces a hinge or joint in the magnetic circuit, which is, of course, very undesirable.

Method 21, moving the armature away from the pole-pieces, is very much easier to accomplish mechanically, and has a great many advantages as a means of regulation. Dr. S. S. Wheeler and myself have been working for some time on motors in which this method of regulation is employed and the results we have obtained have been very satisfactory, in fact, we found it to be extremely simple, effective and reliable.

The second table gives a list of the possible cases of motor regulation which may occur with direct or continuous currents. There are four supremely important quantities or conditions in connection with electric motor regulation—potential, current, speed and load—and it is with reference to one or more of these that practically all motors are designed, built, sold and used. Motors are always distinguished, both in science and in trade as constant potential or constant current motors; constant or variable speed motors, and constant or variable load motors; hence a classification of motors based upon the constancy or variability of these four factors is very convenient, and at the same time scientifically correct. The second table is made upon this plan, and in it the four quantities are represented by their initial letters, $P$, $C$, $S$ and $L$, expressed respectively in volts, amperes, revolutions per minute, and torque in pounds, at one

foot radius, these being the units ordinarily used in practical as well as scientific work. We find that there are in all 16 different cases, in the first four of which the potential is constant; in the second four the potential and current are both constant, in the

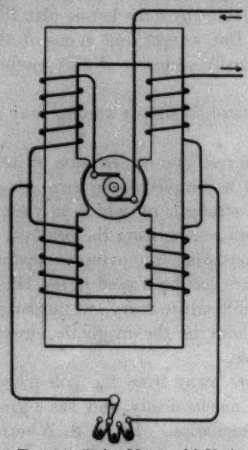

FIG. 7.—Series Motor with Variable Magnetic Shunt.

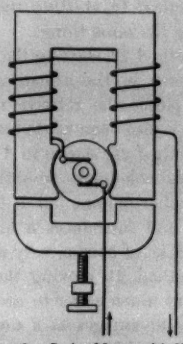

FIG. 8.—Series Motor with Variable Magnetic Short Circuit.

third four the current only is constant, and in the fourth four neither the current nor the potential is constant.

Case 1, in which the potential alone is constant is the case of a series-wound motor, for example, with variable load on a constant potential circuit. Such a motor would rise in speed when the load was reduced and *vice versa*. It would not be at all self-regulating, in fact, it would tend to run at a very high speed with light load, and a very slow speed with a heavy load. It is possible to give various other examples, but one is sufficient in most cases. In this case, however, I may say that the ordinary street car motor, fed from a constant potential circuit, is also an example of case 1, the current being controlled by varying the external or internal resistance, according to one of the methods given in the first table.

Case 2 is that of the ordinary shunt or differential motor, with a variable load on a constant potential circuit. This is self-regulating and maintains a constant speed, as already stated,

and is the commonest case of motor regulation met with. The current varies directly with the load.

Case 3 is that of the ordinary shunt motor with constant load, having a variable resistance in the field magnet. This case is shown in Fig. 1. Increasing resistance of field circuit would weaken field magnetism and motor would run faster and take more current, *i. e.*, current would vary directly with speed.

Case 4 is not a practical one, because, if potential, speed and load are constant, the current cannot be varied without wasting it, that is, any excess of current would be simply destroyed, which, of course, is not permissible.

Case 5 is not likely to occur, because potential and current would not be constant with a variable load and speed, but if it did occur, it would require that the speed and load should vary inversely.

Cases 6 and 7 are not practical for the same reason as given in case 4, because if potential. current and speed were constant, the load could not be reduced without wasting electrical energy, and in case 7, the speed could not be varied without wasting energy.

Case 8 is that in which all four factors are constant, and is best

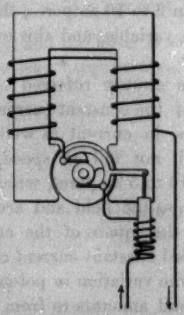

FIG. 9.—Series Motor with Automatic Device for Shifting Brushes.

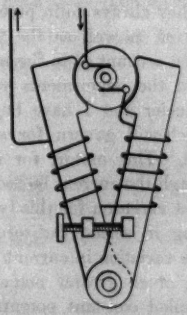

FIG. 10.—Series Motor with Device for Moving Pole Pieces Apart.

illustrated by a shunt motor with constant load on a constant potential circuit, in which case the current and speed would also be constant.

Case 9 may be illustrated by a shunt motor with variable load on a constant current circuit The speed would run up as the load reduced. A more common example is a series motor on constant

current circuit, with switch for cutting out field coils, or, in short, a constant current motor with variable speed and load.

Case 10 is that of the regular constant current or "arc" motor with governor, such, for example, as the Baxter or "C. & C." motor. The ordinary form of this motor is a series machine with a centrifugal governor which operates a switch to cut in and out the field coils, as shown in Fig. 3. This is, next to the shunt and differentially wound motors, the most common and important case of motor regulation.

Case 11 is that of a constant current motor with constant load, with switch for varying field strength. The potential would rise directly with speed, but this case is not likely to occur.

Case 12 is not practical for the same reason as case 4.

The last four cases are those in which both potential and current vary. They are hardly practical cases, because electrical distribution is almost always either constant current or constant potential. It is, however, of course, possible to have cases where both may vary, and examples of each case are given.

Case 13 is one which does occur to a certain extent in practice, for example, if a so-called constant current circuit varies slightly, as they always do in practice, say from 9 to 10 amperes, then the current as well as the potential are variable, and this must be taken account of in the regulation.

In the experiments which I have already referred to, Dr. Wheeler and I have built a motor of the constant current type which will govern for wide variations in current as well as in load. This motor, for example, will not fall in speed, even though the current be reduced from 10 to 5 amperes, which is a great variation for this type of motor, as the field and armature being in series, the torque varies as the square of the current. This variation in current in the so-called constant current circuits is a much greater percentage than the variation in potential of so-called constant potential circuits, and amounts to from $\frac{1}{2}$ to 1 ampere.

Having generally described the different cases of motor regulation, let us take up the mathematical relation of potential current, speed and load, which may be expressed quite simply.

Using the symbols $P$, $C$, $S$ and $L$, as defined above, we have $P \times C$ as the total electrical energy supplied to motor in watts or $\frac{P\,C}{746}$ in horse power. Calling commercial efficiency $a$, the actual

mechanical horse-power developed by a motor is $\frac{a\,P\,C}{746}$ expressed in electrical terms. The equivalent expression in mechanical terms is $\frac{2\,\pi\,S\,L}{33{,}000}$. Since the point at which load $L$ is measured is one foot from centre of shaft and travels $2\,\pi$ feet per revolution, or $2\,\pi\,S$ feet per minute, this multiplied by the load and divided by 33,000, gives horse-power developed by motor.

Thus we have :—

$$\frac{a\,P\,C}{746} = \frac{2\,\pi\,S\,L}{33{,}000} = \text{horse-power of motor.}$$

or

$$P\,C = \frac{746 \times 2\,\pi\,S\,L}{33{,}000 \times a} = \frac{S\,L}{7.04 \times a}$$

For convenience we may write $P\,C = \frac{S\,L}{7a}$ with an error of about one-half of one per cent.

If the efficiency $a$, of motor is 85.2 per cent., the denominator $7.04a$ becomes 6 exactly, and we have $P\,C = \frac{S\,L}{6}$, and if the efficiency is 75.8 per cent., we have $P\,C = \frac{S\,L}{5}$. The former is as high and the latter is as low as is ordinarily met with in practical work, therefore these are the limiting values.

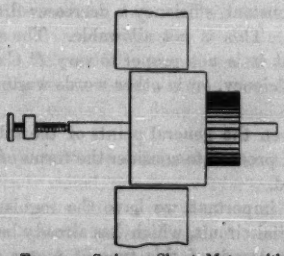

FIG. 11.—Series or Shunt Motor with Regulator for Moving Armature Out of Field.

The equation $P\,C = \frac{S\,L}{7.04a}$ or one of the three simplified forms just given may be advantageously used for solving problems in motor regulation. If we know any four of the quantities we may, of course, find the fifth by simply solving the equation with re-

spect to it. It is also evident that if any three of the quantities are constant then the other two will vary directly or inversely with each other, depending upon their position in the equation. This is the ordinary case we have to deal with in regulation. Usually speed is required to be constant, either potential or current is maintained constant, and efficiency should be practically constant down to very small loads; thus we have either current or potential varying directly with load. The efficiency is rather a confusing element in motor regulation. For this reason it was not introduced as a fifth quantity in the second table, as it would have complicated it and made a great many more possible cases. The efficiency should be high (close to 100 per cent.), and as nearly as possible constant; therefore it would not affect the figures much.

If the load or speed is zero, or very low, the potential or current should be correspondingly reduced and the efficiency would remain constant. This is the condition for perfect regulation. Practically it always takes some current to overcome friction, etc., even when load is zero, in which case efficiency is zero, but this current should be very small.

The equation $P\,C = \frac{S\,L}{7.04a}$ applied to the cases marked "not practical" in second table, shows in case 4 for example, that if $P\,C$ and $L$ are constant, efficiency $a$ decreases directly with reduction in speed. This is not allowable. The same is true of the other cases that it is not proper to vary $P\,C$ or $L$ simply at the expense of efficiency, or in other words waste current to obtain regulation.

Having now given the general points of the subject of motor regulation, we will proceed to consider the forms of motors which are now being used.

First, and most important, we have the regular shunt motor for constant potential circuit, which has already been referred to several times. Thousands of this type of motor are in use and give very satisfactory results. A properly designed motor of this kind will regulate within five per cent., which is near enough for most purposes.

It has no regulating mechanism or complicated circuits to get out of order, and it may be called the ideal self-regulating machine. The next important form is the differentially wound motor, which is even more perfect in closeness of regulation.

Theoretically, it might be made almost absolutely constant in speed, practically the speed varies about two per cent.

These are the figures given me by the company which manufactures these machines in the largest quantity and of the most excellent workmanship. Silvanus Thompson gives an example of one of these machines, which varies only $1\frac{1}{2}$ per cent. in speed, with a variation from 1.1 to 11.14 h. p.

The rule for winding differential motors is that the number of turns in the shunt divided by the number of turns in the series coil, are equal to the resistance of the shunt divided by the sum of the resistance of the armature and the series coil. On this side of the Atlantic this is called "Sprague's law of winding;" on the other side it is called "Ayrton and Perry's rule for winding." The slight variation in speed which does occur is due to the heating of the coils and other slight disturbances. The shunt coil varies slightly in resistance by heat, therefore the series coil should have a few less turns than the rule requires. The heating of the shunt coil weakens the current in it, and consequently the field magnetism, thus increasing the speed of the machine; therefore the motor runs faster after it has been running for some time. The proper way is, of course, to consider the true speed to be that which the motor has in steady running. At first some trouble was experienced in this type of machine, on account of short-circuiting between the series and shunt coils, but this has been overcome by more perfect insulation.

The shunt or differentially-wound machines may be varied in speed by putting resistance in the field circuit, as shown in Fig. 1. This may, of course, be done automatically, or by hand, usually the latter.

The next important type of machine is the constant current motor. As already stated, this is merely a series-wound machine, with switch for cutting in and out the field coils, the latter being operated by an automatic centrifugal governor, as indicated in Fig. 3, or by hand. Various modifications of this type have been made; for example, a reversed coil having a variable resistance in circuit with it, may be used in multiple arc with regular series field winding. If this resistance is very high, the reversed coil has little or no effect; if this resistance is made very low, it will rob the main coil of its current and also neutralize its effect, thereby greatly reducing the strength of the field magnet.

Constant current machines with regulator are now in great

demand for arc circuits; in fact, it is not practical or safe to use a motor on an arc circuit without a regulator. The differential winding of constant current motors to maintain constant speed is not practicable. The solution of it requires, either that the efficiency should be very low, or that storage batteries be used in combination with the winding to maintain a constant difference of potential. Any such plan as this is, of course, very objectionable.

The three types just given are really about the only continuous current motors used to any extent in practice, and it seems that there is at present no demand for any other type.

Nothing has been said of the regulation of alternating current motors, because it is a radically different subject, and, moreover, alternating current motors tend to run synchronously, maintaining a constant speed and regulating themselves.

In conclusion, I would say, that I hope to see this subject taken up by leaders in electrical science, and given the attention which I think it deserves but which it has not yet received.

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DISCUSSION.

THE CHAIRMAN—(Major O. E. MICHAELIS):—Gentlemen, you have heard Mr. Crocker's paper, which I think I may say, in interest, is in thorough harmonic series with its predecessors. The subject is now open for discussion.

MR. TOWNSEND WOLCOTT:—I would like to ask Mr. Crocker if he has ever observed any difference in sparking between moving one brush and moving both brushes. So far as I have seen, in those machines which use but one brush, the sparking is immaterial. I do not know why it should be so. I never worked out any satisfactory theory.

MR. CROCKER:—It would be half as much, certainly, because there would be only one brush instead of two. But very likely there is some further advantage. I have never observed it and therefore never considered it. It is possible there may be some action, but I do not see what it could be. When one or more brushes are off the neutral point they seem to spark in proportion to the amount they are removed from that point.

MR. WOLCOTT:—I can show you a dynamo with one brush on what is supposed to be the proper contact point, and the other one about 100 degrees from it, sparking very little more than it

does when it is set opposite to the first. But this is a dynamo that I am speaking of. I do not know whether the same thing would apply with a motor. This machine is built for 25 lights, and is running two or three lights.

Mr. Edward Weston:—Of course, the sparking between the two sections of the commutator of any machine would be dependent on the difference in potential of the sections in passing out of contact with the brushes. That would depend on the number of sections in the commutator and the total electromotive force. That would still further be complicated by changes in field by moving the brushes. It would be a very complicated question to discuss. I can well understand how you could have a machine in which one brush or both brushes could be moved from the so-called neutral point to the point of no current, and it would practically give no spark, and then again you could have a very heavy spark with some types of machine. With some types of machine, such as the Brush, it could not be done very well.

Mr. Crocker:—I understood Mr. Wolcott to say it was a 25 light dynamo running two or three lights.

Mr. Wolcott:—Yes.

Mr. Crocker:—Of course, in that case the machine was really working with only one-tenth of its normal difference of potential. Therefore the sparking would be reduced just in proportion. It is hardly a fair case if a dynamo is running at only one-tenth of its power. Of course, the sparking and all other effects are changed correspondingly. If the dynamo had been running with its full load of 25 lamps it would probably have sparked as much as any other machine.

Mr. Wolcott:—The current is the same. I understood Mr. Crocker to say that the sparking would be worse as you went away from the correct commutating point; so when you get down to two or three lights it ought to be worse than all.

Mr. Weston:—The sparking is entirely due to the difference of potential between the commutator strips.

Mr. Wolcott:—I should hardly say entirely due to that. When you get a good machine with the brushes on the right point there should be no sparking. Where there is a little it could be accounted for by self-induction of the coils.

Mr. Weston:—If there is any difference of potential between the strips there should certainly be a tendency to spark.

Dr. Schuyler S. Wheeler:—The principal cause of sparking

in motors which are regulated, is the fact that the regulator is constantly changing something—either the magnetism of the armature, or of the field, in order to affect the regulation; and, as soon as that is done, what is called the line of resultant magnetism is changed, and while the brushes have not been moved, the non-sparking point has been moved away from the brushes, and we no longer have the brushes at the neutral point. Of course, there are two causes of sparking—one is the breaking of the circuit between the brush tip and the commutator, and the other is the short circuiting between the commutator bars, produced by the brush touching two bars at the same time. To avoid this short circuiting, which is by far the most serious cause of sparking, the brushes are always placed upon the commutator at the point where there is no difference of potential between the bars. These points, known as the points of commutation, mark the position of the magnetic poles induced in the armature by the joint actions of the field magnetism and of the winding upon the armature. Its position indicates the combined effects of these two efforts, at magnetization, and if the strength of either of them is altered, the position of the resultant polarity in the armature changes. Therefore, whenever we change the intensity of the field or of the armature magnetism we shift the line of resultant magnetism and the brushes are no longer on the right spot. For that reason the method of regulation shown by Mr. Crocker in Figure 6 in which the regulation is produced by shunting the current from the whole machine, thereby keeping the relative strength of the armature and the field the same at all times, has the advantage that it will never cause the motor to spark; because, although it alters the power of the machine, it alters the strength of both the armature and the field equally. The method is very objectionable on account of its destroying a large amount of current, namely, all of the current that is taken away from the armature by the shunt, but it has the advantage described, of not causing sparking.

With other forms of regulation, in which the magnetic strength of the field only is varied, it has been necessary to move the brushes, from time to time as the regulator acts, in order to keep them at the proper point; and in some of the forms of motors the brush holders are mechanically connected to the regulator so as to be moved by it automatically when it changes the field strength.

There is another method of regulation which I have tried experimentally that may be interesting, though it is not at all practical. Figure 12 illustrates the device, which consists of a pair of brushes connected to the terminals of the field winding of an ordinary series motor, and bearing upon a cylindrical piece of copper having long tapering teeth at one end. The spaces between the teeth are insulated and the brushes are so placed that when the cylinder is drawn down by an ordinary centrifugal governor the solid copper is in connection with the brushes and the field magnet coil is short circuited. But when the governor moves the copper cylinder upward on its axis at times when the speed is reduced, the toothed portion of the cylinder comes under the brushes, and the tips of the brushes are in contact with the cylinder and thereby in connection with each other only for a part of the time, and are out of connection the rest of the time. The time in contact and the time out of con-

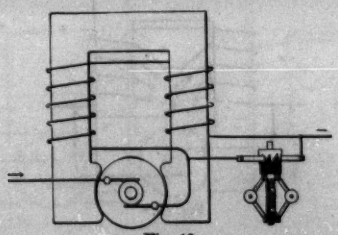

Fig. 12.

tact depends upon the width of the teeth at the point at which the brushes bear upon them, the position of the cylinder being controlled by the action of the governor. Now, it takes some seconds for the magnetism of the field of an ordinary dynamo or motor to change. Consequently, if we make and break this circuit, which short circuits the field very rapidly, we will not lose our magnetism entirely and get it all again; we will simply let down the degree of magnetization, but keep it steady at some point, depending on what proportion of the whole time the circuit is closed and what proportion it is open. That is, if we take a field magnet which requires five seconds to saturate and throw the current on it for one, two, three or four seconds, we will attain different degrees of magnetization below the full strength of the machine, and if we arrange the commutator to put the

current on and off rapidly and make the aggregate time that the current is on one-fifth of the whole time, we will have a uniform magnetization considerably below the maximum, and without the use of any resistance coils whatever. Of course, the device is not at all practicable, the sparking caused by the large field coils being very serious.

Another method (Figure 13) which I think was not touched upon, although it comes under some of those already described as a sub-class, is that employed by the "C. & C." Motor Co. for a hand regulator. It consists of an armature connected in multiple arc with a field which is divided into a large number of coils. The switch is arranged to throw more or less coils out of circuit by simply short circuiting them. This has the double effect of reducing the strength of the field and of shunting the current away from the armature, and thereby reducing the arma

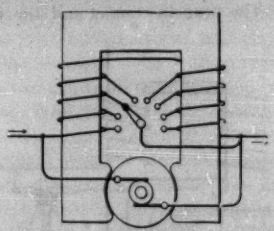

Fig. 13.

ture strength, so that in this we have a machine in which the armature is regulated when the machine is operating on a constant current circuit, without the use of any special devices on the armature. By making the first coil of the field of heavy wire and each succeeding coil of a size finer, a machine is made in which the armature and field magnetisms are reduced in some thing like equal proportions by the action of the switch, and this is done without the use of any outside electrical resistance; but this method has the very serious objection which is sometimes fatal, that the minute the armature speeds up, its counter E. M. F. alters the proportion in which the current divides between the armature and the field circuits. Motors on this plan have been made, however, in considerable numbers, and the reason why this disturbance produced by the counter E. M. F. is not more serious is because the resistance of the field coils may be propor-

tioned to correspond properly with the increases of armature speed, which are apportioned to the several contacts.

The differential winding mentioned in the last part of Mr. Crocker's paper, as one of the methods of regulating constant current motors, consists of two *opposing* field windings with a set of resistances connected in series with one of them for determining which of the opposing windings shall predominate. (See Fig. 14.)

There is one other form of regulator, a method invented by Sprague, in which the field coil is permanently connected with the line and the armature terminals are connected by switch to various points on the field, the speed of the machine being regulated by sliding the armature terminals from the centre contacts towards the extremities of the field, which weakens the field and strengthens the armature. (See Fig. 15.)

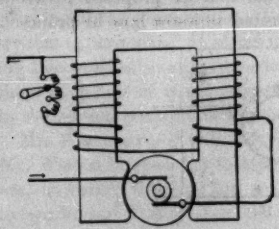

Fig. 14.

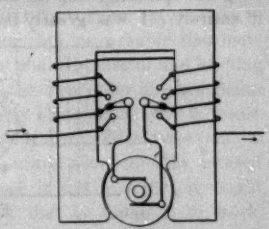

Fig. 15.

Mr. Joseph Wetzler:—I would like to ask Mr. Crocker whether he has ever considered the Waterhouse 3-brush regulation as applied to motors. If so, I would like to hear what his opinion is in reference to it.

Mr. Crocker:—I have considered the matter somewhat, but I never went into it at all deeply. It never was a very attractive method of regulation to me, but I cannot say positively whether it would work or not. I think very likely it would. The condition in a constant current motor is very similar to that in an arc light dynamo. If a certain regulation is good for an arc light dynamo it is probably equally good for a constant current motor. That is quite universally true. But of course this cannot be laid down as an absolute rule. You would have to apply it in each particular case before you are sure. But on general principles it is true.

Mr. C. O. Mailloux:—There is a very peculiar fact with reference to 3-brush regulation, in connection with the sparking, which was brought to my attention a year or two ago. I am sorry that Mr. Hamilton, the former chief electrician of the Western Union, is not here, because he is the man who made the discovery, if it may be called a discovery. (See Fig. 16.) I had occasion to design a machine for telegraphic work where it was expected to use a third brush for the purpose of getting varying electro-motive forces: assuming the total electro-motive force to be say 20 volts, then he proposed to use a third brush between the other two and move that brush so that we could get different currents. He could fix it so that there would be either 10 on each side or else 5 on one side and 15 on the other side. As sometimes one-half would not be working and the other half would be working, it was a question whether there would not be great sparking, but he told me that he proposed to avoid it entirely. I was greatly interested to know how he proposed

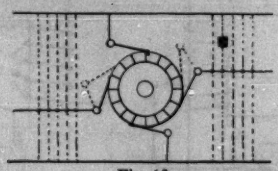

Fig. 16.

to do it, and to my great surprise I found that he had done so entirely by this simple expedient of putting another brush on the opposite side and connecting the two together through a simple galvanometer. Now, we found by practice that as long as these two brushes touched correspondingly so that they were of equal potential, with no current passing through that galvanometer, there was absolutely no sparking. If we moved one connection, and if there was no appliance between the two there would be very excessive sparking, but in any case it did not matter where the brushes were located, provided that they were located at corresponding points. For instance, if he wanted to get only a small potential on one side, he might have one brush touch here and the other brush would have to be moved opposite. I cannot account for the phenomenon; perhaps somebody here may. It was interesting as showing that there is yet a great deal of mystery to be elucidated about the sparking of dynamo brushes.

PROF. E. P. ROBERTS:—I would suggest that Prof. Nichols be called upon in reference to that mode of regulating.

PROF. E. L. NICHOLS:—I am much obliged for the compliment, but I really have little to add to what has already been said. Mr. Crocker's opinion that any device for the regulation of dynamos may be applied to motors with chances of success at least, I concur in. The behavior of third brush regulator machines is a pretty complex question, and depends upon a great variety of facts which we are scarcely yet masters of. We have been studying that at Cornell to some extent and have gained some light on the subject, but it is hardly in a condition to be presented here.

MR. WESTON:—The last case given by Mr. Mailloux would certainly be very singular. I am entirely at a loss to understand it. Under the conditions named it would indicate that the difference of potential between the strips had nothing to do with the sparking of the commutator. I shall take the first opportunity to try that experiment. It seems to me very remarkable that moving two brushes on opposite sides of the commutator and keeping them at points of equal potential, the two other brushes being in the normal position, could possibly bring about such a result

MR. MAILLOUX:—I will only say that I myself said the same as Mr. Weston in speaking to Mr. Hamilton about it. He assured me, however, that he had reasoned it out and that it ought to work, and I only state the fact that he found it to work. There were several persons present and the experiments were very extended. As I stated before I regret that Mr. Hamilton is not here himself to give the details and his explanation of the fact. I have given the experiment as nearly as possible as I remember it. It is nearly two years since it occurred. The dynamo was a large machine, probably having a capacity of ten or fifteen horse power, and it was tried under large variations of load. The machine was intended to supply local circuits for telegraph work, and as we know, there might be a large number on or there might be none, and the great aim was to avoid sparking. If I mistake not the machine was put into practical use at Pittsburgh and may be there yet for all I know. I think it is giving satisfaction. Of course (referring to the figure) I should state that the galvanometer is only used for adjustment and that the two brushes are connected by a metallic conductor of low resistance so that the current supplied to the circuit is derived in equal pro-

portions from both of the two additional brushes. The same thing could be accomplished by connecting a portion of the circuit to each brush.

THE PRESIDENT :—(PROF. ELIHU THOMPSON.) It is my experience that in designing and working the dynamo there is no machine so capable of giving unexpected results. If none of the other members have anything further to say I would like to make a few remarks on the general subject.

Mr. Crocker mentioned that in one of his cases the movement of the brushes in the motor would produce violent sparking. Now, I take exception to that. I say that sparking of that kind is within control, as is the case in dynamos which are built for constant current. Take for instance the modified Gramme form known as the American dynamo, in which by a proper adjustment of the over-reach or over-lap of the brushes, you can displace them enormously and still get no sparking. Apply the same process to a motor and move the brushes and you will get the same condition. The sparking at the brushes as I take it depends on conditions of balance, giving the exact time that is needed for current in the coil which is going under the brush to lose the current it has been carrying and take up the opposite current. If you give that time exactly, in any case, you will get no sparking, as in this case your field is constant and your armature current is also constant there would be nothing to prevent such a balance being preserved at all times. In other words, if we commute our currents in the armature bobbins in a certain density of field and in shifting the brushes do not disturb the conditions, or if we do disturb those conditions, but bring into action other conditions which will adapt the machine to the state of field or the state of commutation, then you can control the sparking. In other words, the self-induction is the thing you have to take into account. It takes time in any armature section to reverse the current, and we know that on one side of the brush the current is in one direction and on the other side in another direction. Keep then the coil under the brush for just that time which allows it to pass from 5 amperes which it may be carrying on one side to 5 amperes which it may be carrying on the other side, and you have no sparking in any case. That is one reason why flexibility exists in many forms of dynamo, especially where the armature has some influence on the disposition of the magnetic forces. In cases in which the field is abundantly strong and the

armature is a weak magnet, then of course, the commutation is made in a rather weak field just before the bobbin reaches the strong field. But if the armature bobbin has passed forward under the field, then the conditions are all changed.

I would like to add also another case to Mr. Crocker's cases—one which I worked at for some time and which I found was a fairly satisfactory solution of the problem of constant current motors. I have not very much faith in constant current motors anyhow. They always require some extraneous mechanism like a governor or something of the kind which varies the conditions and that governor is apt to be behind time, especially on light loads. It may set the motor oscillating. The case is very similar in constant current motors to what we find with arc lamps on constant potential. We have instability with arc lamps on constant potential, and we have instability with motors on constant current, for the simple reason that the lowering of speed in the

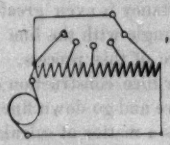

Fig. 17.

motor drops the counter-electro-motive force and we only have a definite certain current to work on; that means a drop in the actual amount of energy available. The time the motor needs more energy to bring up its speed is the time it loses the energy, and that is analogous to the rush of current that will go through an arc lamp put in multiple on a constant potential circuit, because the resistance of the arc falls with the increase of the current. Consequently the more current passes the more current will pass as hot vapor is produced. The case which I referred to as an additional case is one for constant current with the field wound in shunt with the armature. It is shown in Figure 17. We have the field in shunt with the armature but we vary the field coils in the size of wire. We start with thick wire, then thinner until we end with a rather thin wire. We now make our connections from this at various points and put a governor on the motor shaft which will give us a contact to traverse these

connections. The armature and field being in shunt the current will always divide between them, and it will be seen that when we have this contact over one side we have a comparatively high resistance field, or in other words, we have something like a shunt machine; that will be the condition under heavy load. As the load comes off and the speed rises the connection passes to the other end. We get then a low resistance field. The current passes through the field branch in greater proportion than through the armature branch. The field being low resistance is economical, and we get in that way a very fair and economical regulation for series motors. I have built motors on that plan and found they worked very satisfactorily indeed, with a proper arrangement for moving the contacts. There is another advantage that I find in such a motor, that the brushes are practically sparkless. That is, they may be set in one position, require no movement at all, even on so few segments as a three-coil armature, and of course on a Gramme armature and a multiple segment machine the constancy is even greater, but the brushes are simply set at a certain angle with the line joining the fields, and the governor takes care of this process. The objection to it is that it requires a rather nice construction of the machine. You begin with a coarse wire and go down finer and finer, and to get the grading properly is a matter of calculation, of course. (This is the same method of regulation as Figure 14, described by Dr. Wheeler).

Mr. Crocker:—I would like to add one word. I think there is a great difference between motors and dynamos in one respect, and it is a purely practical one; the dynamo is handled by men who know how to handle machines; you can afford to have dynamos in the hands of skilled workmen. Whereas motors are exactly the opposite; they are likely to be in the hands of the most ignorant people. Therefore systems of regulation which are perfectly allowable or practical in the case of a dynamo are not so allowable or practical in the case of a motor. In fact, the case spoken of with a nice balance in the position of the brushes is all right in the case of a dynamo where it can be maintained but it probably could not be maintained in the case of a motor.

In speaking of shifting the brushes I referred more to motors than to dynamos. I was not talking of dynamos or criticising dynamo regulation, I think that motor regulation is very different in the respect I have stated, and that is about the only radical

difference that there is between motor and dynamo regulation.

THE PRESIDENT:—I would say that in working the carbon brushes we find we can have quite large variations on account of the resistance of the brush. The spark will be almost insignificant, because the resistance of the brush is opposed to any sparking or short-circuiting.

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NOTE.—The proceedings of the General Meeting will be continued in the double number for August and September.

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&c. (February, 1889.)

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**Telegraphy Without Wires.** (Corr.) A. A. Campbell Swinton, F. Higgins. *Lond. Elecn.*, Feb. 1, p. 378.

**Electrical Coast Communication.** *Lond. Elec. Engr.*, Feb. 15, p. 15.

**Electrical Signaling on Board Ship.** (Note.) J. B. Willis. *Pall Mall Gazette; Lond. Elec. Engr.*, Feb. 22, p. 149.

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**Instruments for Measuring High Potentials.** (Ill.) *Elec. World*, Feb. 9, p. 69. (Thomson's Voltmeter; Ayrton & Perry's Voltmeter; Carpentier's Voltmeters)

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**Executions by Electricity.** *Elec. World*, Feb. 2, p. 60.

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**An Electrical Fare Register.** (Note.) *Lond. Elec. Rev.*, Feb. 22, p. 218.

**The Electric Blowpipe.** (Ill.) Samuel Sheldon. *Sci. Am.*, Feb. 2, p. 68; *Elec. World*, Feb. 16, p. 88; *West. Elecn.*, Feb. 9, p. 68; *Lond. Elec. Rev.*, Feb. 15, p. 189.

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**An Electric Railway Switch.** (Col. Le Grand.) *Md. Lt. & Ht.*, Feb. 21, p. 207.

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**Electricity, Ether and Ponderable Matter.** Sir Wm. Thomson. Inst. Elec. Engrs. (Concl'd from p. 334.) *Lond. Elecn.*, Feb. 1, p. 362. (Corr.) O. C. D. Ross. Feb. 1, p. 380. *N. Y. Elec. Rev.*, Feb. 23, p. 6.

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**Chicago Electric Club.** *West. Elecn.*, Feb. 16, p. 91.

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**Electricity in the University of Rochester.** Otis H. Robinson. *West. Elecn.*, Feb. 16, p. 82.

**The Effect on U. S. Patent of Prior Foreign Patent.** Ed. C. Davidson. *Elec. World*, Feb. 9, p. 68.

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**Statistics of Patents on Electrical and Related Inventions Issued from the U. S. Patent Office in 1888.** T. D. Lockwood. *N. Y. Elec. Engr.*, Feb., p. 61; *Lond. Elec. Rev.*, Feb. 22, p. 208.

**Thickness of Insulations.** Alexander Thompson. *West. Elecn.*, Feb. 9, p. 74; *Lond. Elec. Rev.*, Feb. 22, p. 210.

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**"The Steam Engine."** E. N. Dickerson. Elec. Club. *N. Y. Elec. Rev.*, Feb. 16, p. 10.

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